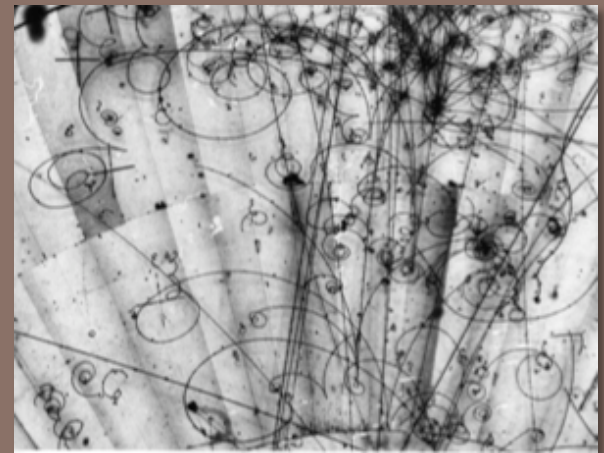# NEUTRINO CROSS SECTIONS

Sam Zeller

Fermilab

PANIC 2011

July 26, 2011

- this topic has become quite interesting lately
- revisiting ν scattering physics again for 1st time in decades
- new data is revealing some surprises

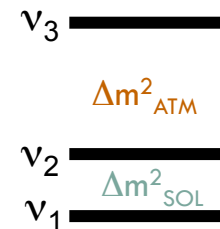# Neutrino Physics

- looking forward, there are some big ?'s we will be trying to answer …

  - what are the masses of neutrinos?

  - are neutrinos their own anti-particles?

  - is θ_{23} maximal? is θ_{13} non-zero?

  - what is their mass ordering?

  - is CP violated in the ν sector?

  ν_3 ▬▬▬▬

  Δm^2_{ATM}

  ν_2 ▬▬▬▬
  Δm^2_{SOL}
  ν_1 ▬▬▬▬

- extensive international effort aimed at addressing these ?'s will place even greater demands on our knowledge of underlying ν interactions

  (this knowledge will quickly become inadequate as aim for next level in precision & search for smaller and smaller effects)

S. Zeller, PANIC, July 26, 2011

Neutrino Cross Sections

- pursuit of ν oscillations has unfortunately forced us into a rather complex region of ν interaction physics

  (100's MeV to few-GeV)

- lots of rich physics here; is where are also building our future ν oscillation experiments

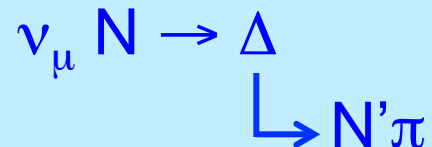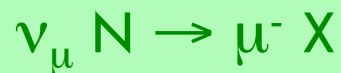 *(broad band beams contain contributions from multiple reaction mechanisms)*

(across 3 orders of magnitude) G.P. Zeller

S. Zeller, PANIC, July 26, 2011
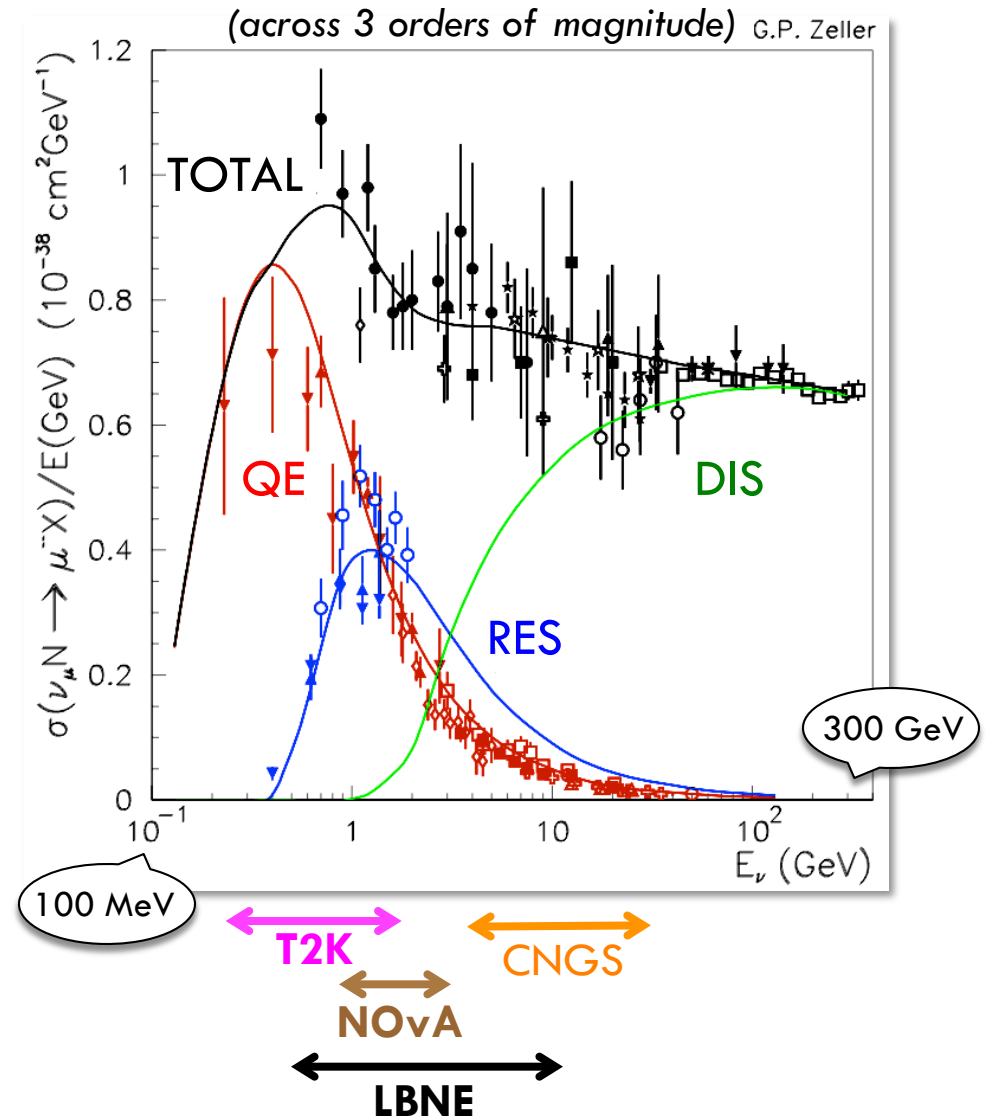
Why Is this Complicated?

quasi-elastic

$\nu_\mu\, n \rightarrow \mu^-\, p$

resonance production

$\nu_\mu\, N \rightarrow \Delta$
$ \hookrightarrow N'\pi$

deep inelastic scattering

$\nu_\mu\, N \rightarrow \mu^-\, X$

need to extrapolate into low energy region

G.P. Zeller

TOTAL

QE

RES

DIS

300 GeV

100 MeV

T2K

NOvA

CNGS

LBNE

$\sigma(\nu_\mu N \rightarrow \mu^- X)/E(\text{GeV})$ ($10^{-38}\ \text{cm}^2 \text{GeV}^{-1}$)

E_ν (GeV)
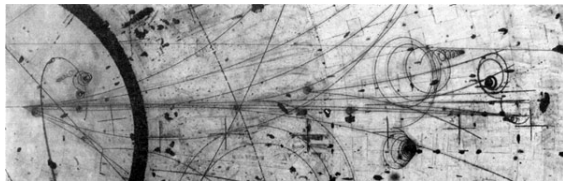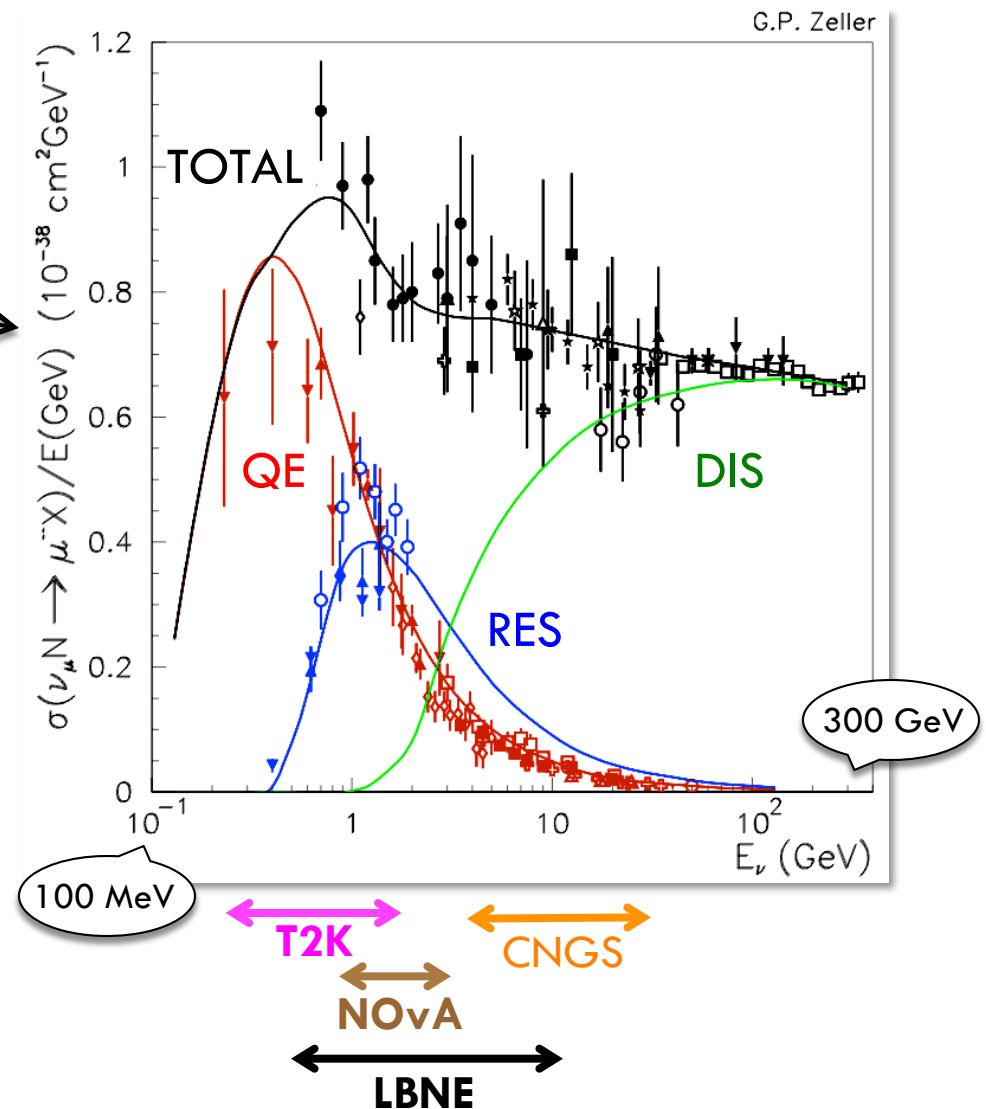
S. Zeller, PANIC, July 26, 2011
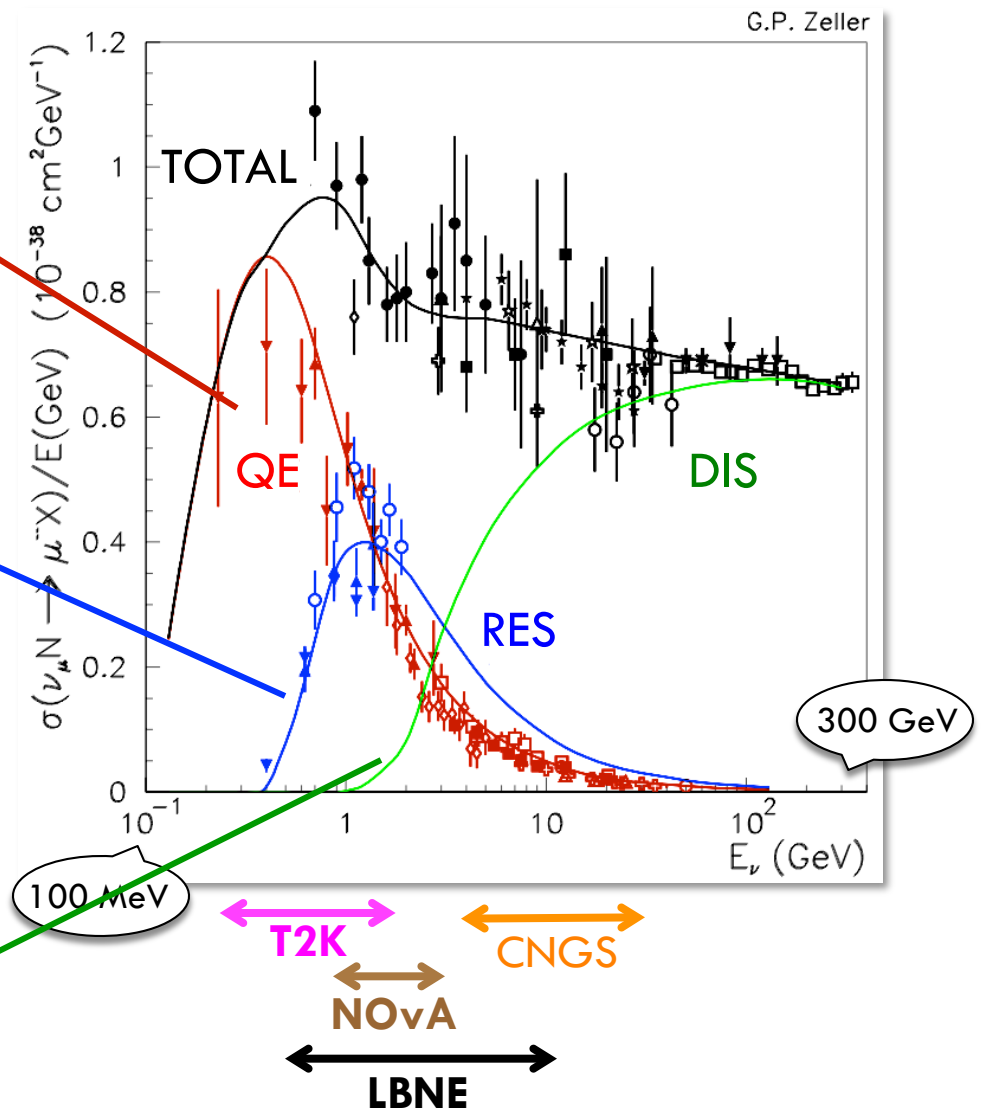
Historical Measurements

- region where exp'l knowledge of σ_ν has been limited

- most of info in this region comes from data that is >30 yrs old
  - *low statistics*
  - *mostly D_2, H_2 bubble chambers*

- one crucial difference: modern experiments use heavier nuclei

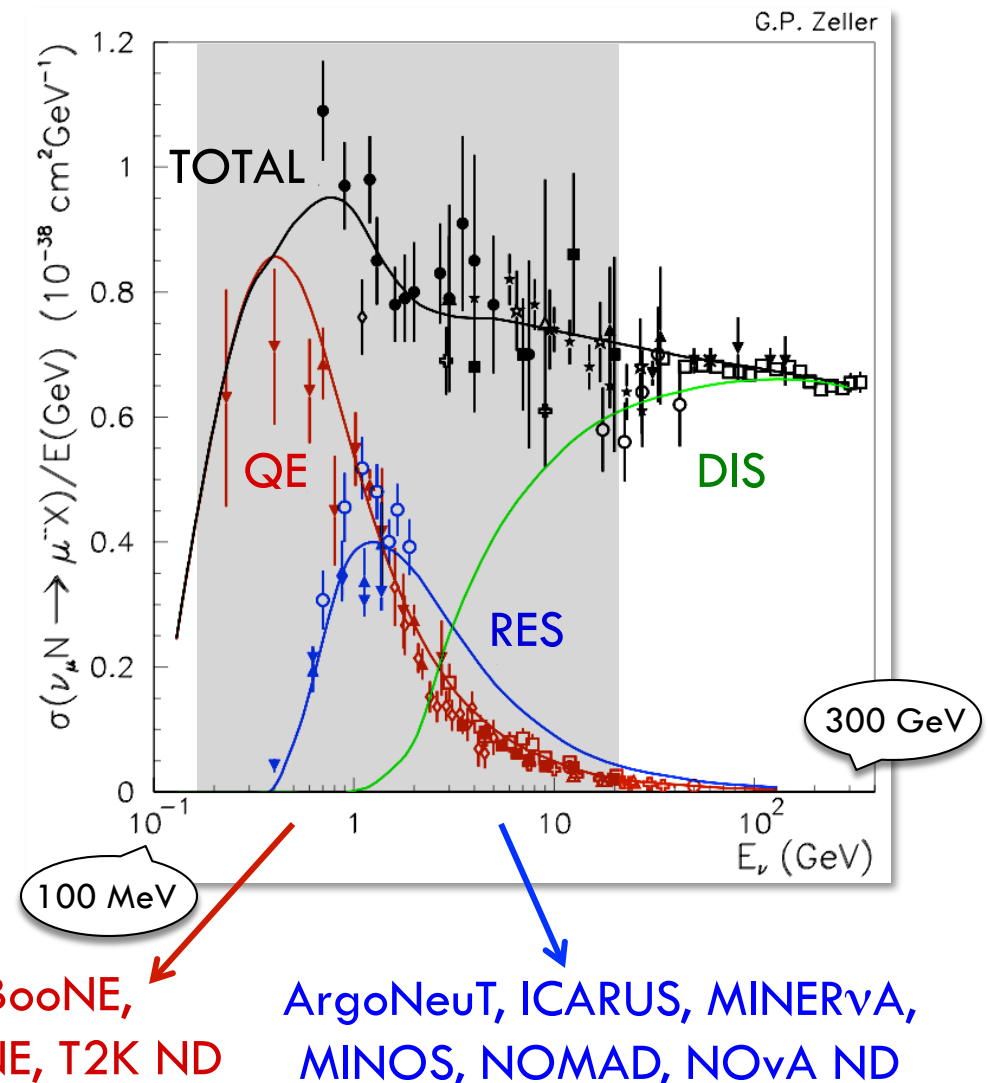- has necessitated a dedicated campaign of new measurements

G.P. Zeller

Modern Measurements

- new experiments making improved σ_ν measurements cover a broad E range

- <u>advantages of new data:</u>
  - nuclear targets *(crucial!)*
  - higher statistics
  - intense, well-known ν beams
  - studying ν and $\overline{\nu}$'s
    (will be important for C̸P̸)

G.P. Zeller

TOTAL

QE

RES

DIS

300 GeV

100 MeV

K2K ND, MicroBooNE, MiniBooNE, SciBooNE, T2K ND

ArgoNeuT, ICARUS, MINERνA, MINOS, NOMAD, NOvA ND
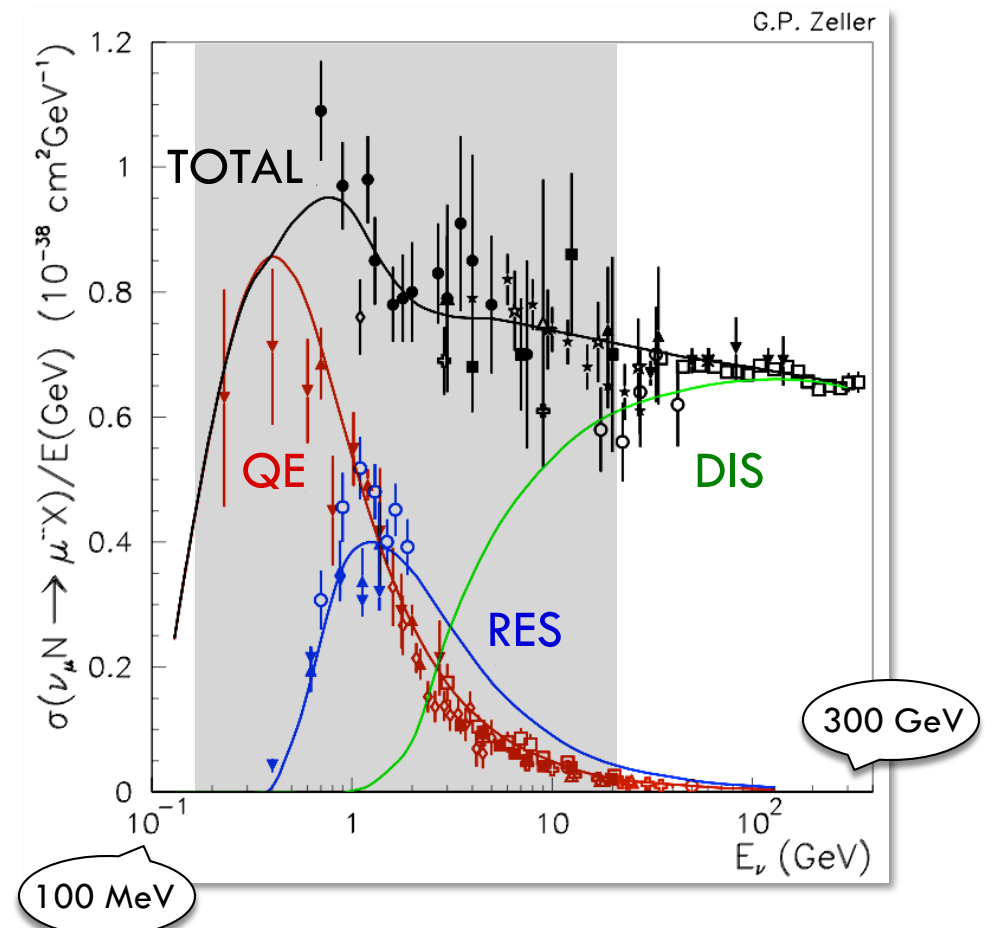
Neutrino Interactions

- let's start on the left and work our way up in energy …

    - QE
    - π production
    - CC inclusive

- use this plot as our guide as we survey the landscape

- what have we learned in exploring this region again 30+ years later? … along the way, will also point out next steps …
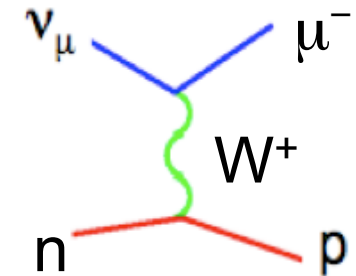
Quasi-Elastic Scattering

Why important?

$$\nu_\mu \, n \rightarrow \mu^- \, p$$

(single knock-out nucleon)

- **important for ν oscillation experiments**

  - typically gives largest contribution to
    signal samples in many osc exps (atm+accel)

  - one of the most basic ν interactions

- examples:

  signal events

  $$\nu_\mu \rightarrow \nu_e \ (\nu_e \text{ appearance})$$

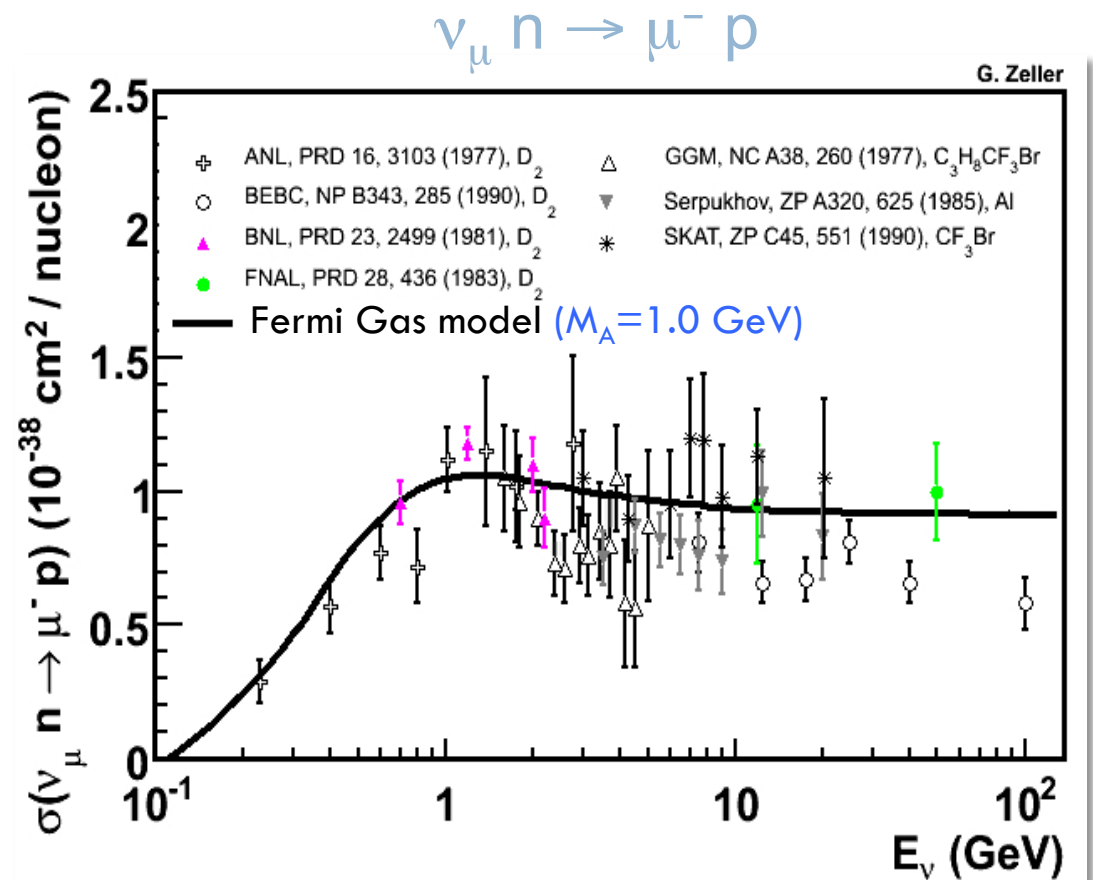 $$\nu_\mu \rightarrow \nu_X \ (\nu_\mu \text{ disappearance})$$

S. Zeller, PANIC, July 26, 2011

Historical Context

- **conventional wisdom** is that

  QE σ is well-known

  - *it's a simple 2-body process*

- **can consistently describe**
  all the experimental data

  - *most is on D_2*

  - *assume scattering takes place on individual nucleons*

  - *Fermi Gas model*

  - *$M_A = 1.0$ GeV*

- **this description has been**
 quite successful

  - *can predict size & shape of σ*

$\nu_\mu\ n \rightarrow \mu^-\ p$

G. Zeller

ANL, PRD 16, 3103 (1977), D_2 △ GGM, NC A38, 260 (1977), $C_3H_8CF_3Br$
BEBC, NP B343, 285 (1990), D_2 ▼ Serpukhov, ZP A320, 625 (1985), Al
BNL, PRD 23, 2499 (1981), D_2 ✳ SKAT, ZP C45, 551 (1990), CF_3Br
FNAL, PRD 28, 436 (1983), D_2
Fermi Gas model (M_A=1.0 GeV)

$\sigma(\nu_\mu\ n \rightarrow \mu^-\ p)$ (10^{-38} cm^2 / nucleon)

E_ν (GeV)

with these ingredients, it looked straightforward to describe ν QE scattering on nuclei

QE Cross Section on Carbon

- this has now been repeated

(T. Katori)

- MiniBooNE

* NOMAD

σ (cm^2)

$E_\nu^{QE,RFG}$ (GeV)
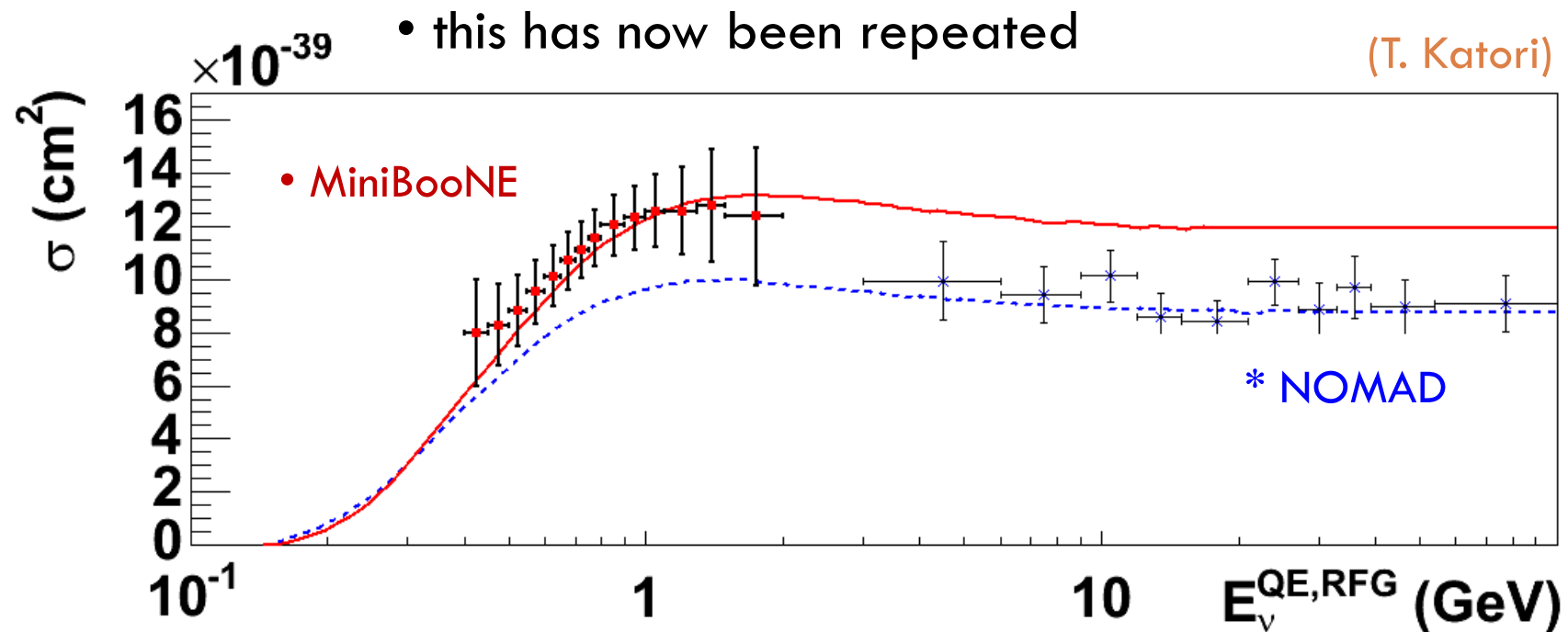
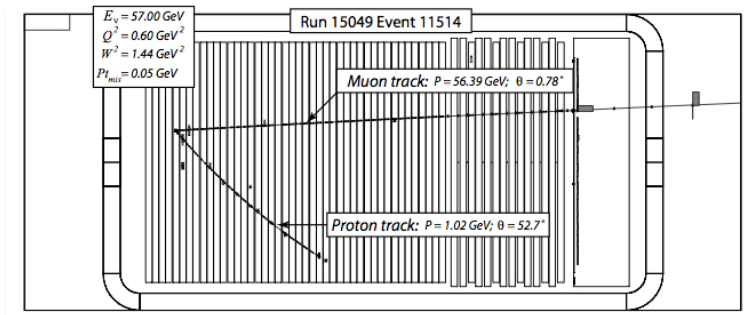**MiniBooNE 2002-present:**

Aguilar-Arevalo *et al.*, PRD **81**, 092005 (2010)
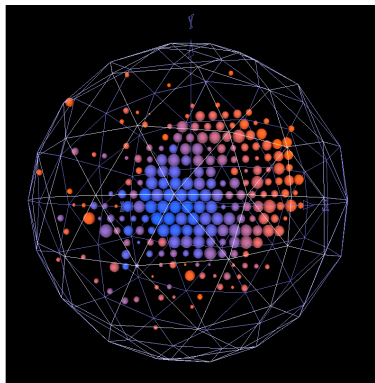
NOMAD 1995-1998:

Lyubushkin *et al.*, EPJ **C63**, 355 (2009)

S. Zeller, PANIC, July 26, 2011
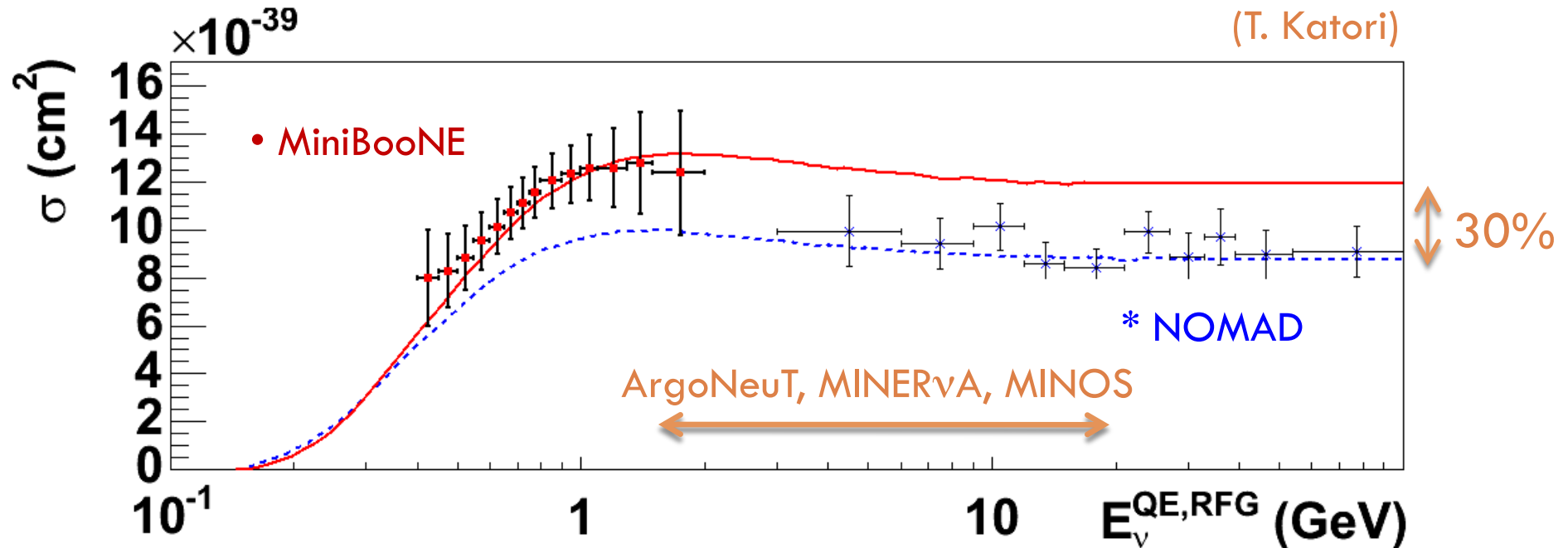
QE Cross Section on Carbon

(T. Katori)
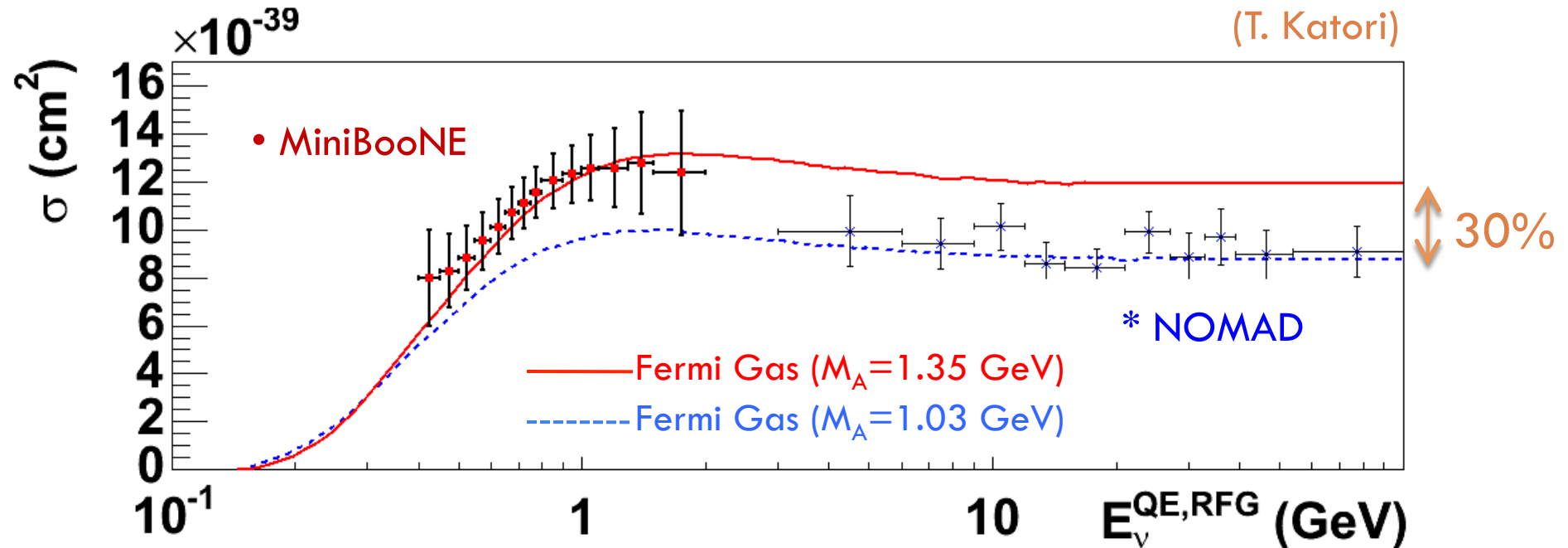
- MiniBooNE data is well above "standard" QE prediction
  (increasing M_A can reproduce σ)

- NOMAD data consistent with "standard" QE prediction
  (with M_A=1.03 GeV)

QE Cross Section on Carbon

(T. Katori)

- MiniBooNE
- * NOMAD
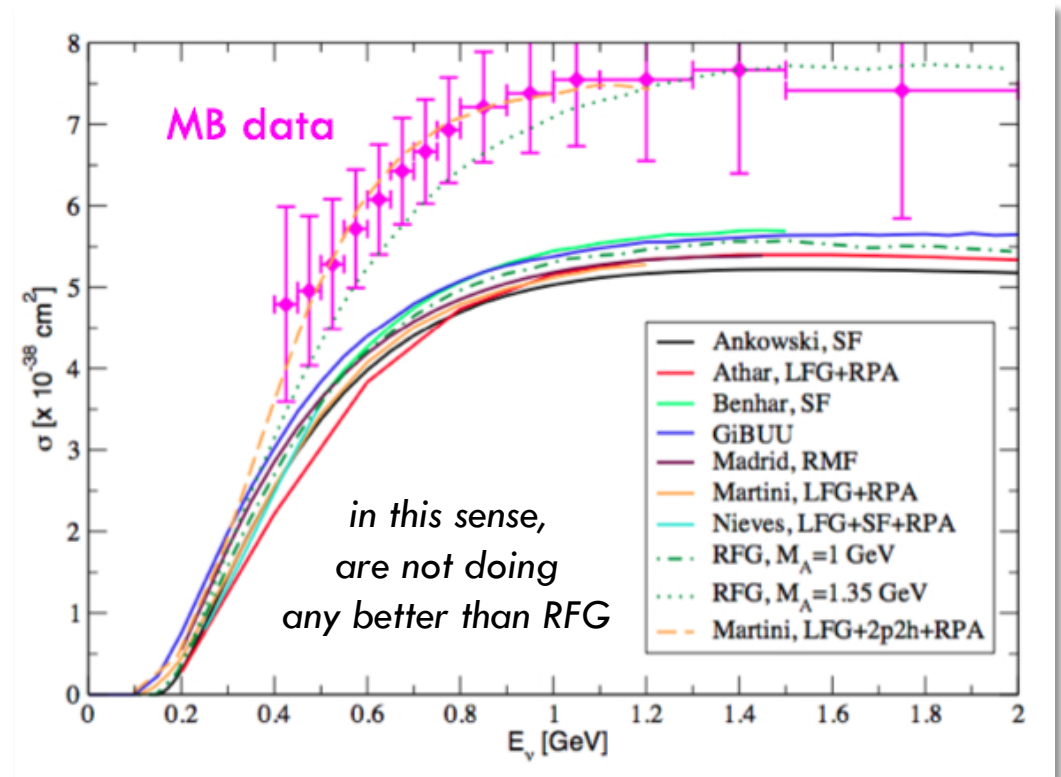- ArgoNeuT, MINERνA, MINOS
- 30%

- results of low & high E experiments appear to be inconsistent; cannot be described with a single prediction *(we'll come back to this)*

- good news: new data will be weighing in on this soon
  (will show some preliminary QE results from MINERνA)

QE Cross Section at Low Energy

- MiniBooNE data has provided the 1st measurement of ν QE scattering on a nuclear target heavier than D_2 at low E_ν (E_ν<2 GeV)

  - *naturally, these results have garnered a lot of attention lately, largely because they were unexpected*
  (effects first seen in K2K ND)

- more sophisticated models also underpredict the low E σ
  (fall short by 30-40%!)

- remedy has been to increase M_A in these predictions

in this sense, are not doing any better than RFG

Legend:
- Ankowski, SF
- Athar, LFG+RPA
- Benhar, SF
- GiBUU
- Madrid, RMF
- Martini, LFG+RPA
- Nieves, LFG+SF+RPA
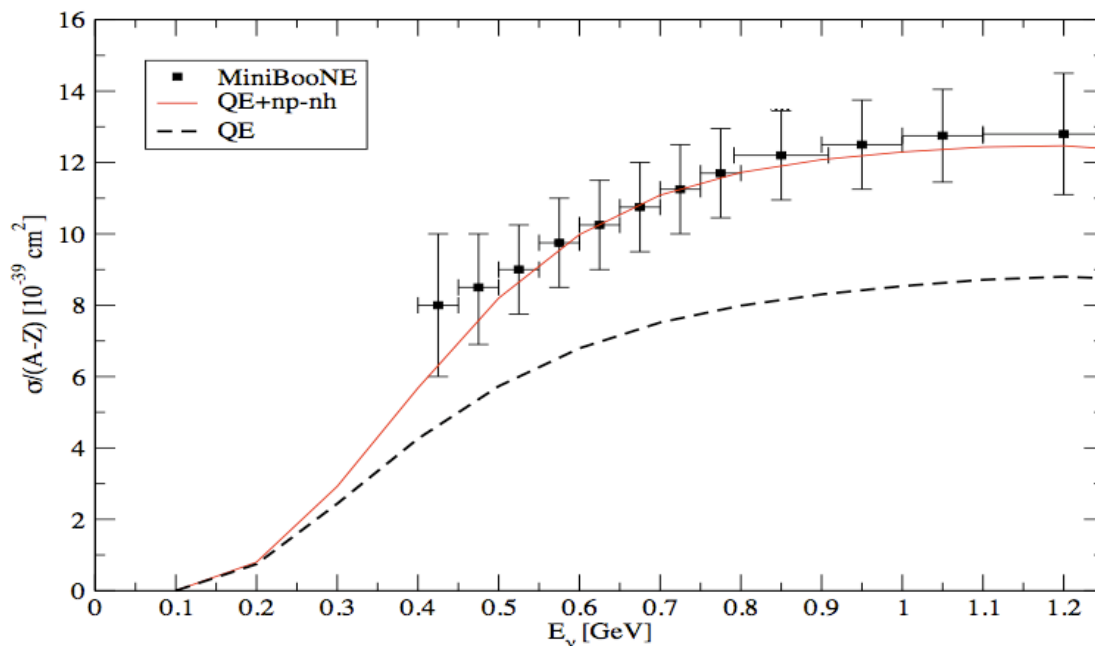- RFG, M_A=1 GeV
- RFG, M_A=1.35 GeV
- Martini, LFG+2p2h+RPA

(L. Alvarez-Ruso, NuFact11)

Nuclear Effects to the Rescue?

- another possible explanation has recently emerged

- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …

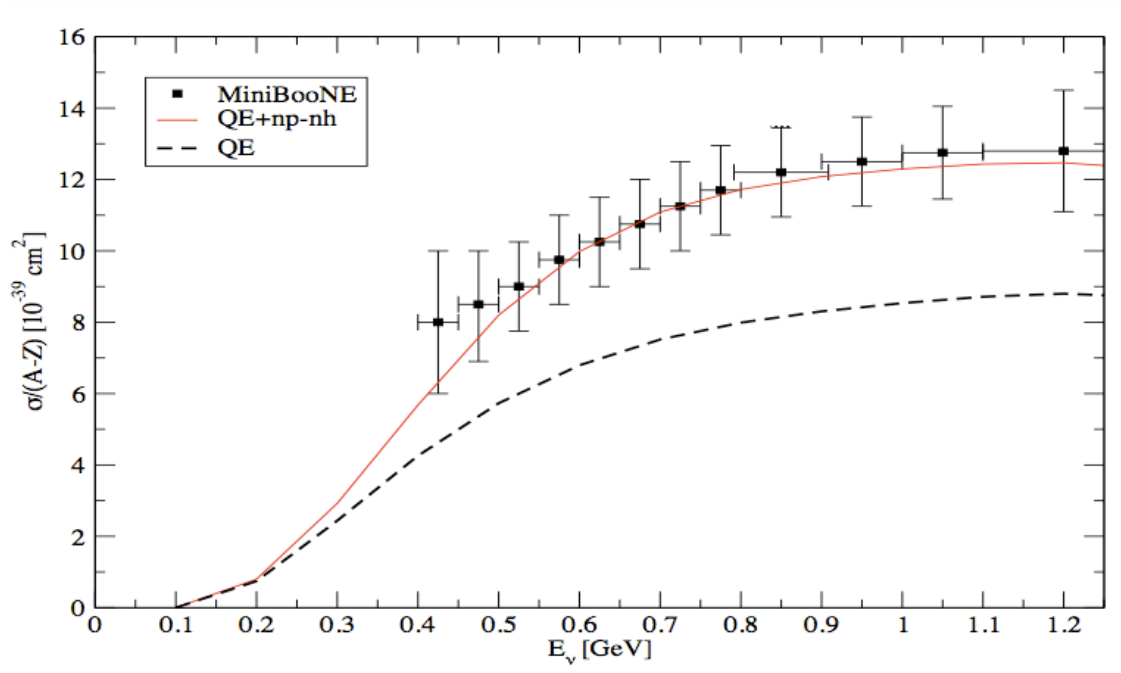Martini *et al.*, PRC **80**, 065001 (2009)

- extra contributions coming from <u>nucleon correlations</u> in the nucleus

  (all prior calculations assume nucleons are independent particles)

- can predict MiniBooNE data without having to increase M_A *(here, $M_A=1.0$ GeV)*

Nuclear Effects to the Rescue?

- another possible explanation has recently emerged

- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …

Martini et al., PRC **80**, 065001 (2009)

- idea is not new

  - Dekker et al., PLB **266**, 249 (1991)
  - Singh, Oset, NP **A542**, 587 (1992)
  - Gil et al., NP **A627**, 543 (1997)
  - J. Marteau, NPPS **112**, 203 (2002)
  - Nieves et al., PRC **70**, 055503 (2004)

calculation first came out in 2001
before MB started taking data

Nuclear Effects to the Rescue?

- another possible explanation has recently emerged

- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …
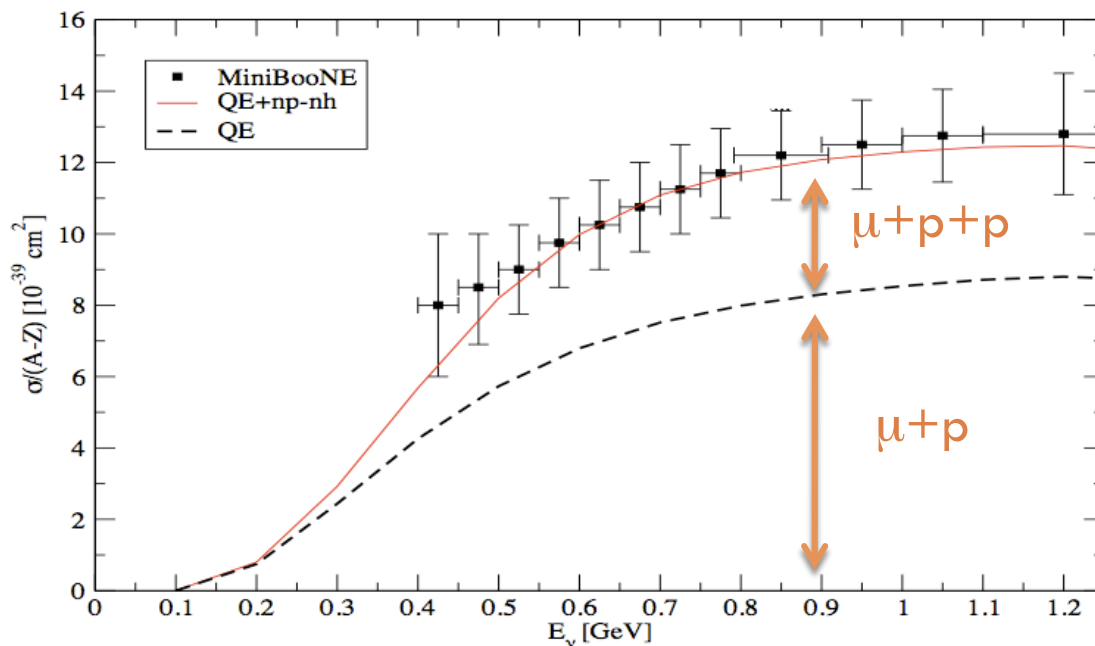

μ+p
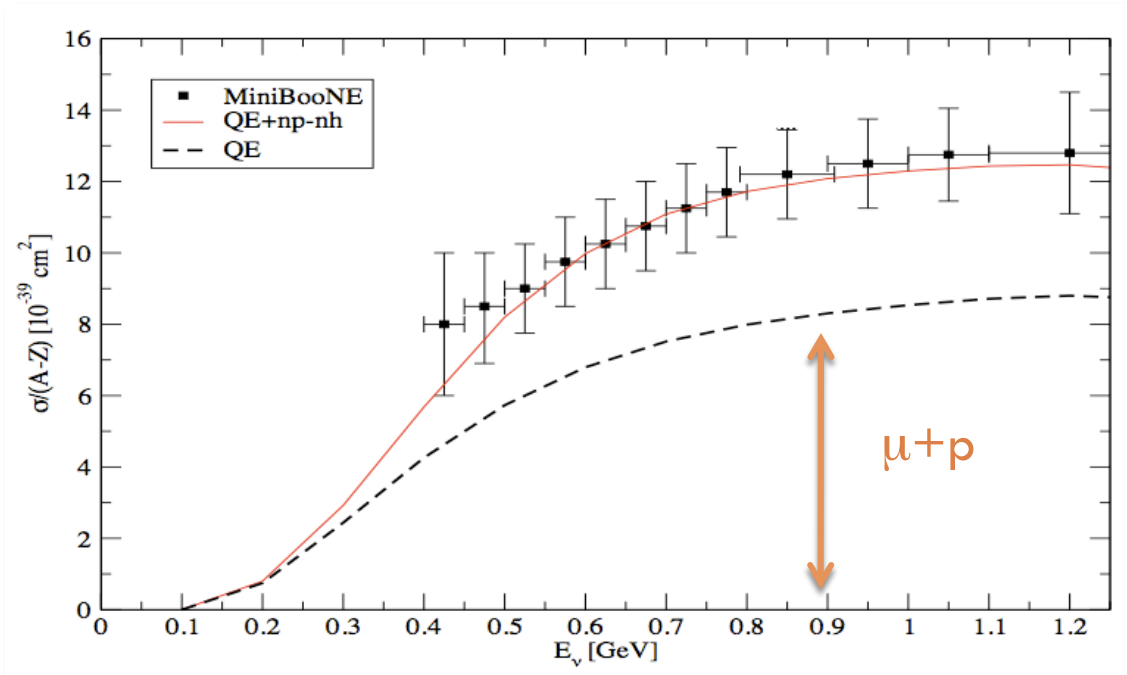
← "standard" QE prediction we saw earlier

Martini *et al.*, PRC **80**, 065001 (2009)

Nuclear Effects to the Rescue?

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- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …

Martini *et al.*, PRC **80**, 065001 (2009)

add'l nuclear processes contribute ~40% more σ at these ν energies and produce a multi-nucleon final state ($\mu+p+p$)
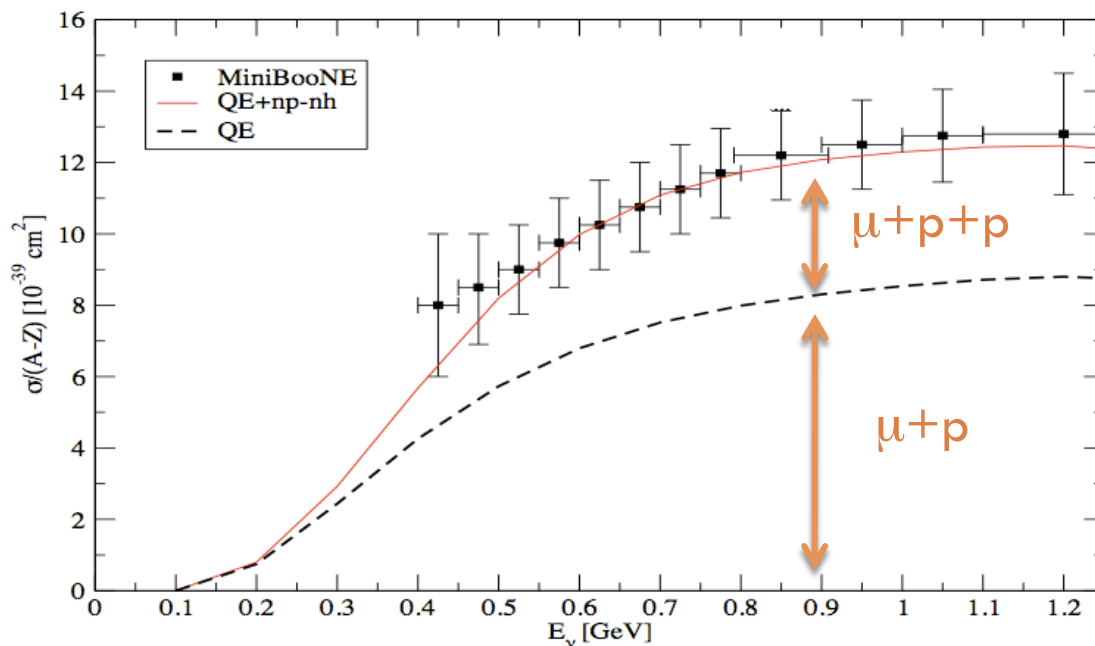
- together account for MB

these two final states are indistinguishable in MB and in Cerenkov detectors in general

Nuclear Effects to the Rescue?

- another possible explanation has recently emerged

- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …

μ+p+p

μ+p

Martini *et al.*, PRC **80**, 065001 (2009)

- could this explain the difference between MiniBooNE & NOMAD?

jury is still out on this

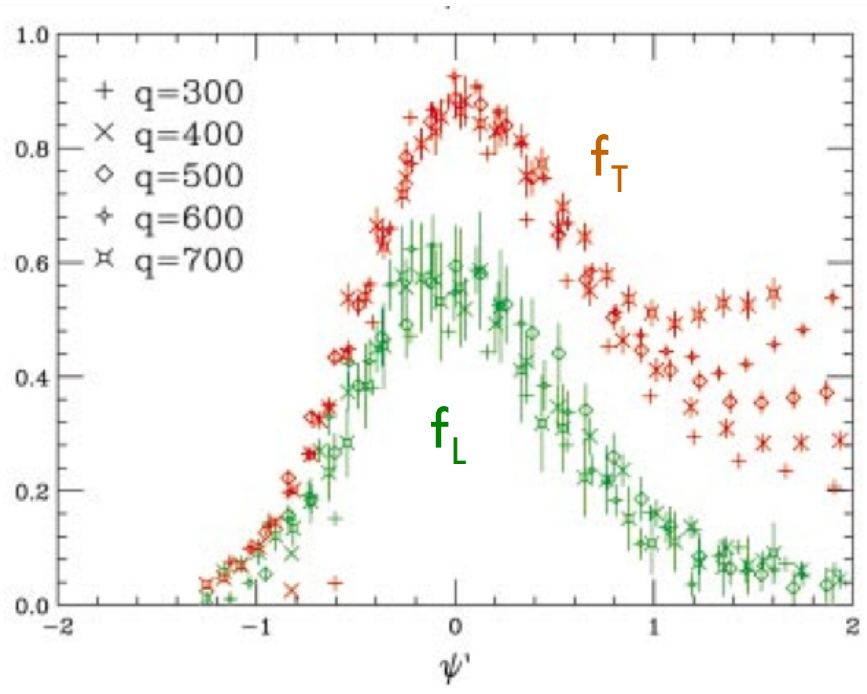need to be clear what we mean by "QE" when scattering off nuclear targets!

Electron QE Scattering

- supporting evidence from electron QE scattering
  (J. Carlson, G. Garvey)

f_T

f_L

Carlson *et al.*, PRC **65**, 024002 (2002)

- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons

- in contrast, a significant increase observed in **transverse** component
  (can be explained by SRC and 2-body currents)

- has been known for over a decade, seemingly forgotten

- implies that there should also be a corresponding transverse enhancement in ν QE scattering!

New Approach

- calculation of additional nuclear dynamics (nucleon correlations & 2-body currents) in the treatment of ν QE scattering has been a recent focus in last year:

  - Nieves *et al.*, arXiv:1106.5374 [hep-ph]
  - Bodek *et al.*, arXiv:1106.0340 [hep-ph]
  - Amaro, *et al.*, arXiv:1104.5446 [nucl-th]
  - Antonov, *et al.*, arXiv:1104.0125
  - Benhar, *et al.*, arXiv:1103.0987 [nucl-th]
  - Meucci, *et al.*, Phys. Rev. **C83**, 064614 (2011)
  - Ankowski, *et al.*, Phys. Rev. **C83**, 054616 (2011)
  - Nieves, *et al.*, Phys. Rev. **C83**, 045501 (2011)
  - Amaro, *et al.*, arXiv:1012.4265 [hep-ex]
  - Alvarez-Ruso, arXiv:1012.3871[nucl-th]
  - Benhar, arXiv:1012.2032 [nucl-th]
  - Martinez, *et al.*, Phys. Lett **B697**, 477 (2011)
  - Amaro, *et al.*, Phys. Lett **B696**, 151 (2011)
  - Martini, *et al.*, Phys. Rev **C81**, 045502 (2010)

(work to incorporate increased transverse response from e⁻ A. Bodek, parallel 2E)
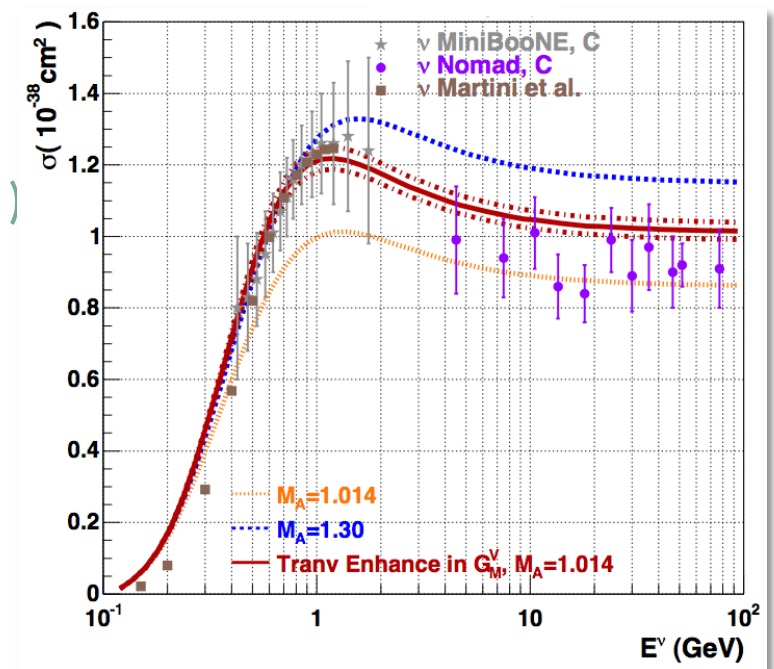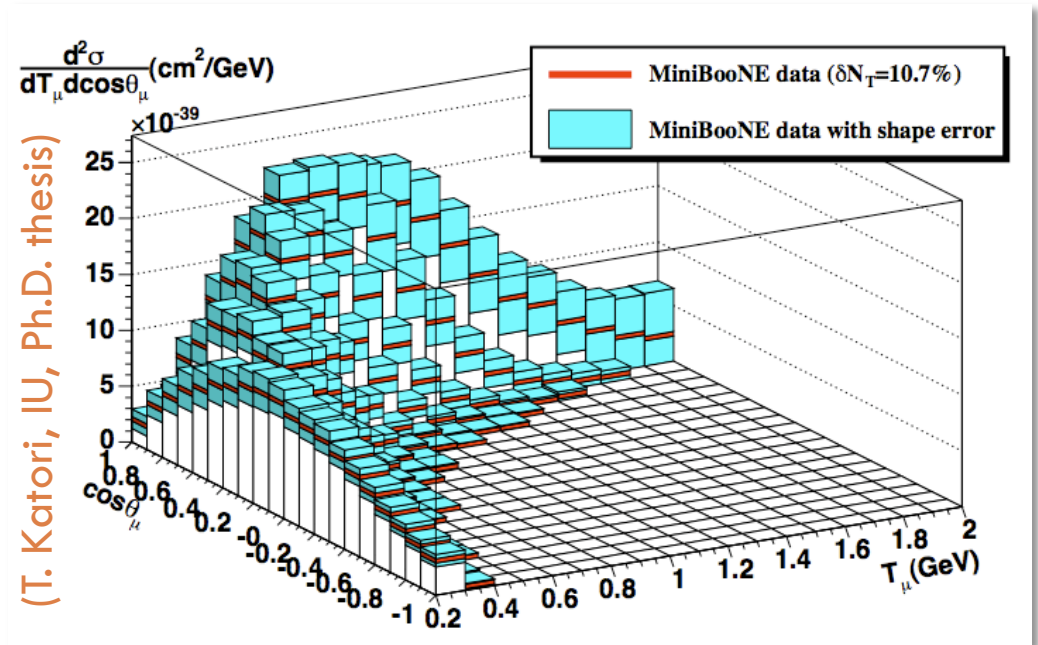
Moving Forward

- 146,000 ν_μ "QE" events
  (currently world's largest sample)

- 1st double differential σ's
  (from MiniBooNE)

  $$d^2\sigma/dT_\mu d\theta_\mu$$

- historically, never had
  enough statistics to do this

Aguilar-Arevalo *et al.*, PRD **81,** 092005 (2010)

(T. Katori, IU, Ph.D. thesis)

- provides much richer info than $\sigma(E_\nu)$ & less model-dependent

- posing a formidable challenge for new nuclear model calcs
  (need more data like this ... not only μ but also measurements of p kinematics!)

wish list

Direct Evidence

- e⁻ scattering experiments have already provided evidence for SRC

 *big splash in Science magazine: R. Subedi et al., Science **320**, 1476 (2008)*
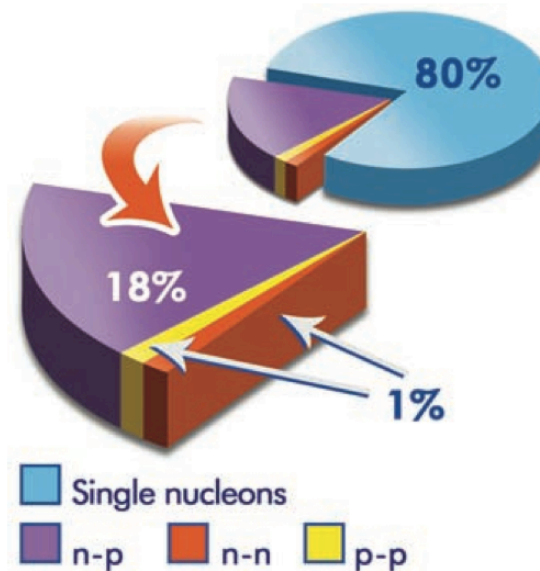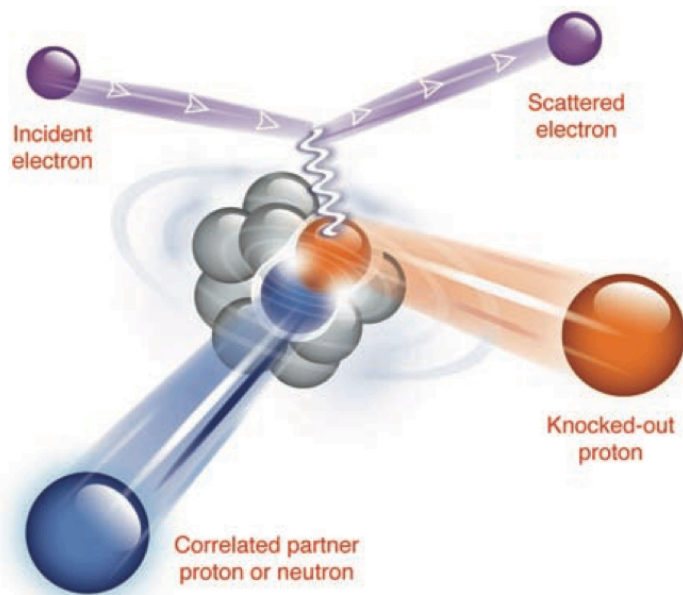
~20% of nucleons in carbon are in a correlated state

- direct measurement of multi-nucleon final states in a ν detector with low thresholds could play an important role in quantifying scattering from such correlated nucleon states (NOMAD, Veltri *et al.*, NP **B609,** 255 (2001))
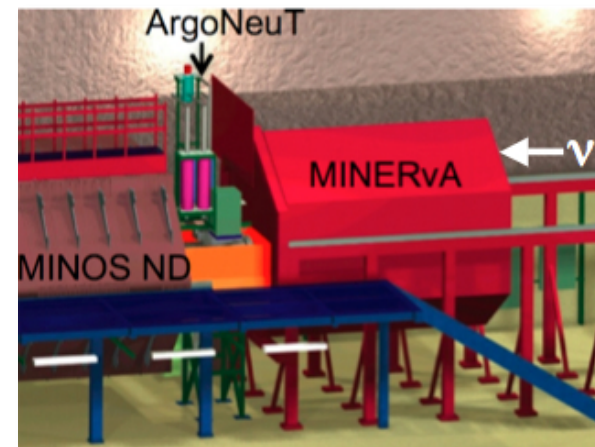
QE Scattering in a Liquid Argon TPC

μ+p

μ+p+p

μ+p+p+p
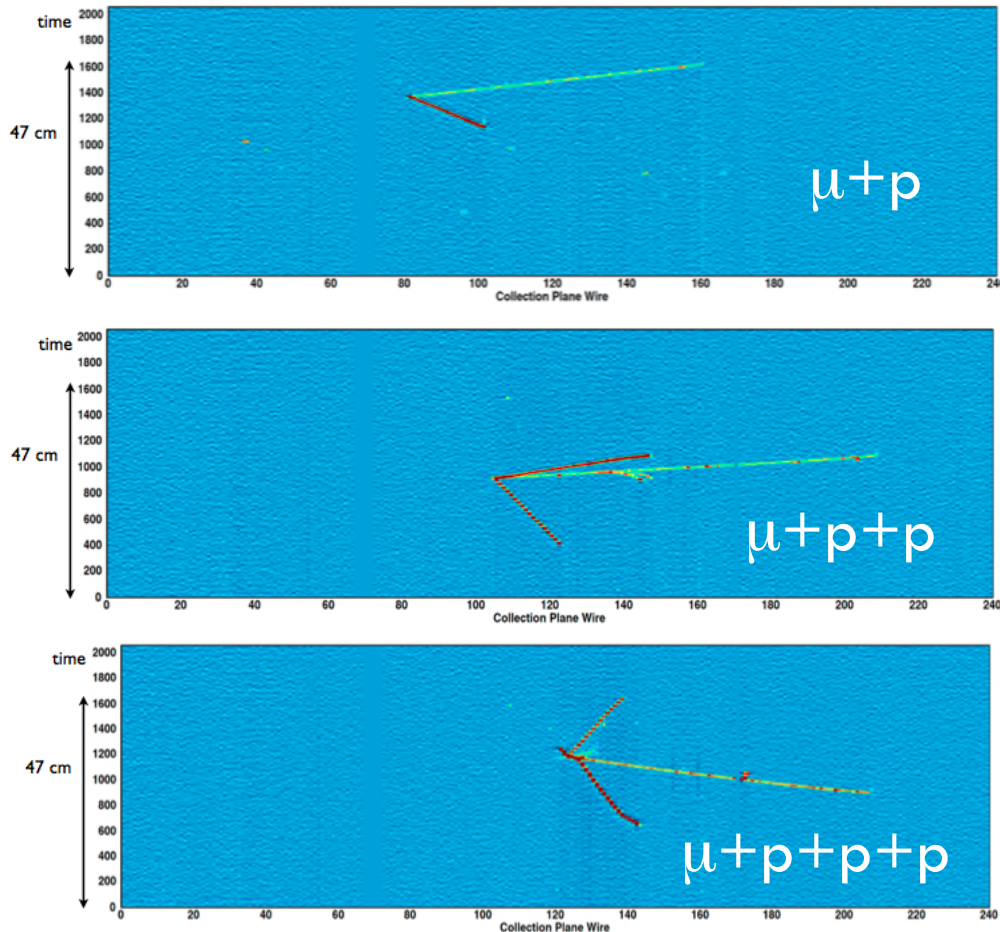
J. Spitz, arXiv:1009.2515 [hep-ex]
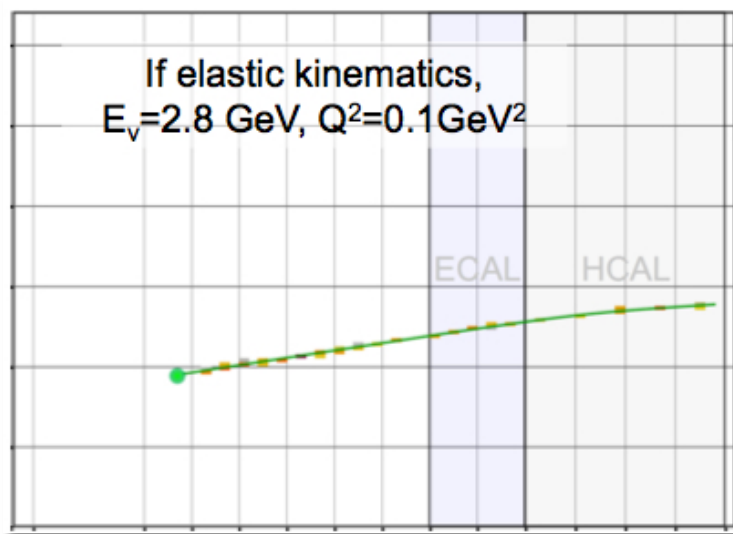
- **ArgoNeuT** = 175L LAr TPC in NuMI beam (2009-2010)

- ν interactions in exquisite detail
  (ex., can detect protons down to 50 MeV)

- plus data from **ICARUS, μBooNE**

- need to disentangle SRC from FSI

$\overline{\nu}$ QE at MINERνA!

If elastic kinematics,
$E_\nu = 2.8$ GeV, $Q^2 = 0.1$ GeV^2

ECAL   HCAL

$\overline{\nu}_\mu\, p \rightarrow \mu^+\, n$

- will pursue a broad range of σ_ν's with multiple beam E's and nuclear targets
  (much of focus up to now has been on O, C)

- starting data-taking with full detector in Mar 2010

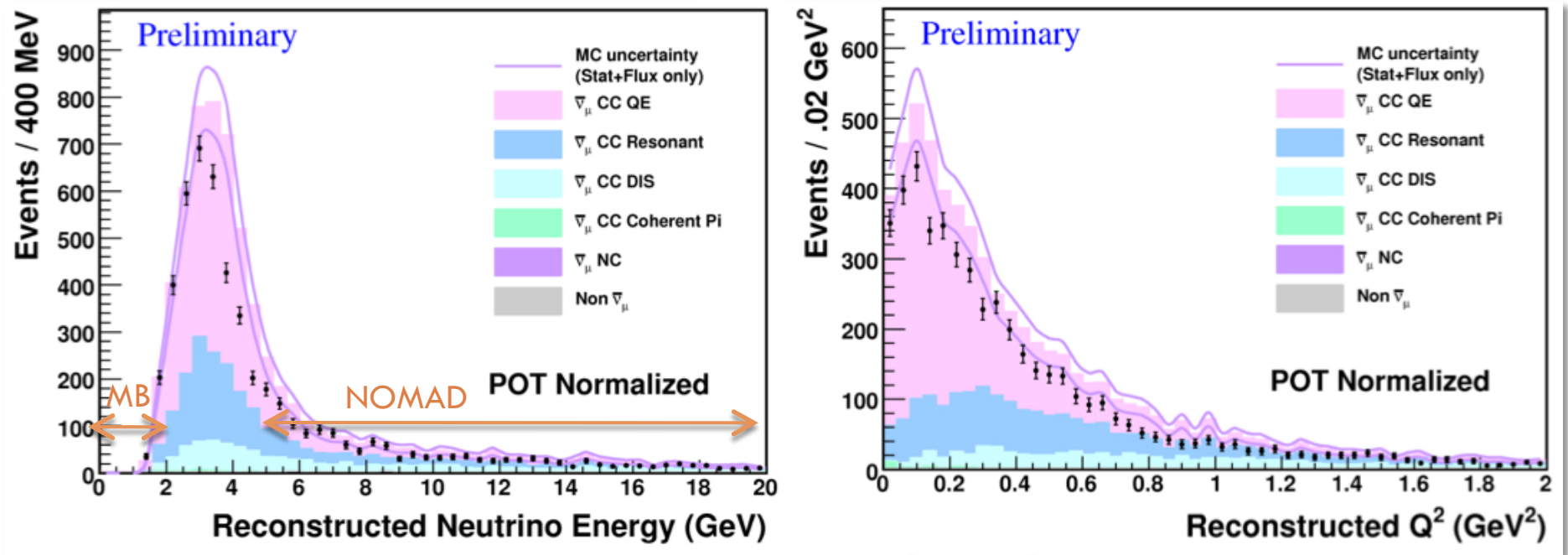*(R. Ransome, parallel 2E)*

nuclear targets (He, C, Fe, Pb, H$_2$O, CH)

- starting with $\overline{\nu}$ QE analysis; for a tracking detector has some advantages: unlike ν case:

  - less sensitive to details of the event selection (n in f.s.)

  - less ambiguity as to whether or not selection includes extra effects of nucleon-nucleon correlations (produces an n+n in f.s.)

$\overline{\nu}$ QE at MINERνA

(K, McFarland, NuInt11)

- $\overline{\nu}_\mu$ QE interactions in CH across a large energy range

  (note: MiniBooNE ν_μ QE: 0.4-2 GeV, NOMAD: 4.5-60 GeV)

- observe an event **deficit;** not fully understood

  (relative to "standard" QE MC, GENIE, M_A=0.99 GeV, untuned NuMI flux)

determining ν flux using special run data, add'l stats, ν QE, different selections
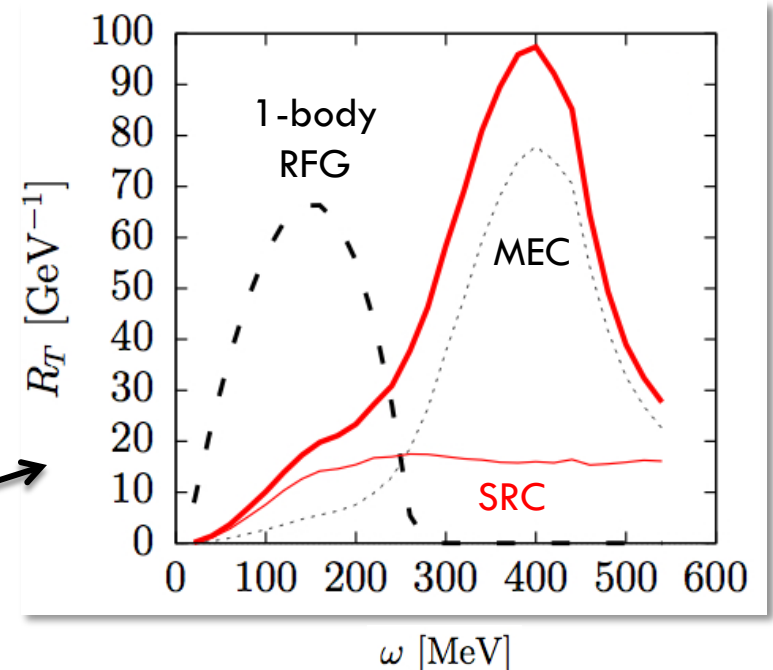
This is Important

- something as simple as QE scattering is not so simple

  - nuclear effects can significantly <u>increase</u> the cross section
  - idea that could be missing ~40% of σ is a big deal!

- <u>good news</u>: expect larger event yields

- <u>bad news</u>: need to understand/simulate the underlying physics

- effects will be different for ν vs. $\overline{\nu}$

  (at worse, could produce a spurious $\not{C}P$ effect)

- can impact E_ν reconstruction

Amaro *et al.*, PRC **82**, 044601 (2010)

This is Important

- something as simple as QE scattering is not so simple

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- <u>bad news</u>: need to understa...
  the underlying physics

- effects will be different for ν vs...

  (at worse, could produce a spurious $\not{C}P$ effect)

- can impact E_ν reconstruction

in the past year,
have gone from a
general complacency
that we know the QE σ_ν
to having uncovered a
host of rich nuclear effects

...500 600

ω [MeV]

...r., PRC **82**, 044601 (2010)

Pion Production (Δ, N* → N π)

- NC π^0 production

  (background for ν_e appearance)

  ν_μ → ν_μ

  Z^0

  n,p → n,p π^0

- CC π^+, π^0 production

  (background for ν_μ disappearance)

  ν_μ → μ^-

  W^+

  n,p → n,p π^+

G.P. Zeller

TOTAL

QE

RES

DIS
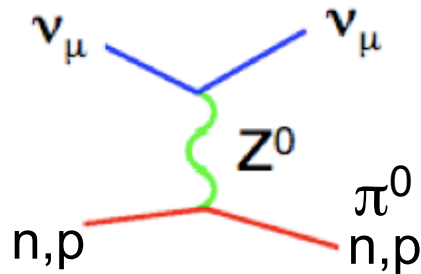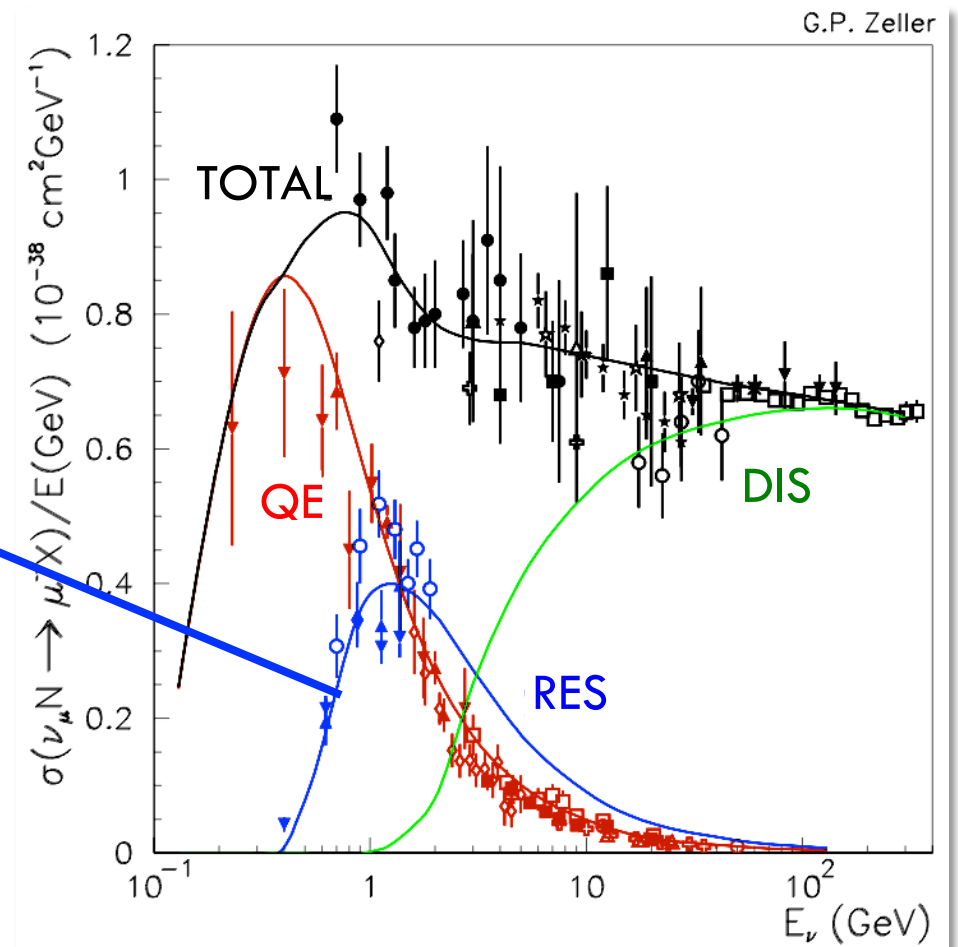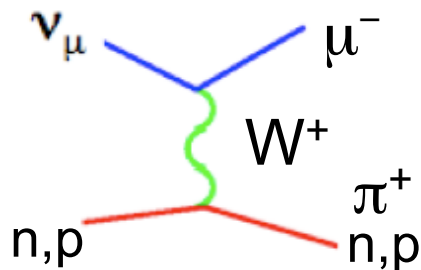
- important for different reasons → backgrounds

Final State Effects

- new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

- once a hadron is produced, is has
  to make it out of the target nucleus

- nucleon rescattering

- π absorption & charge exchange
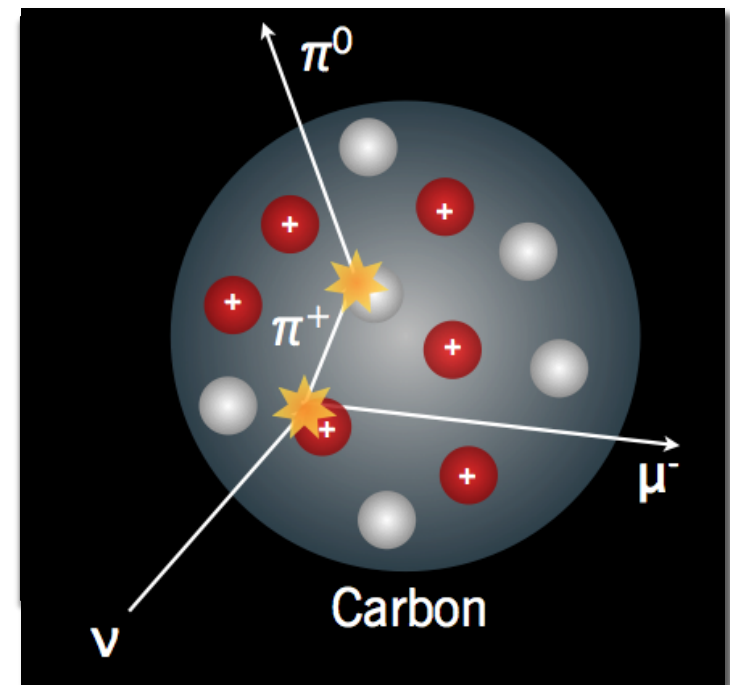
you will have to model final state effects

- have to worry about these effects
- for ν, is a subject that needs more attention
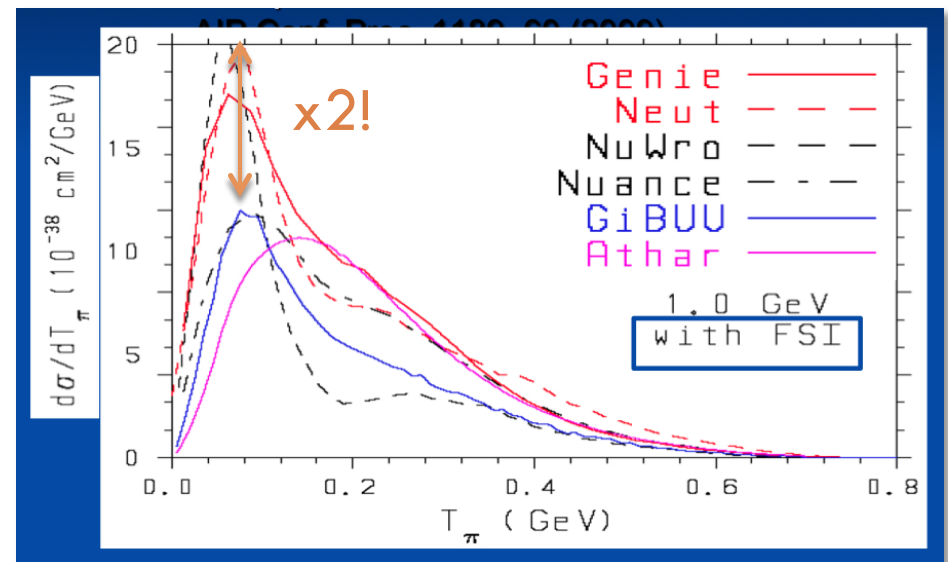 *(U. Mosel, parallel 5F, Thursday)*

Final State Effects

- <u>distortions are large</u>

- important for predicting π^0 bkgs in ν_e searches
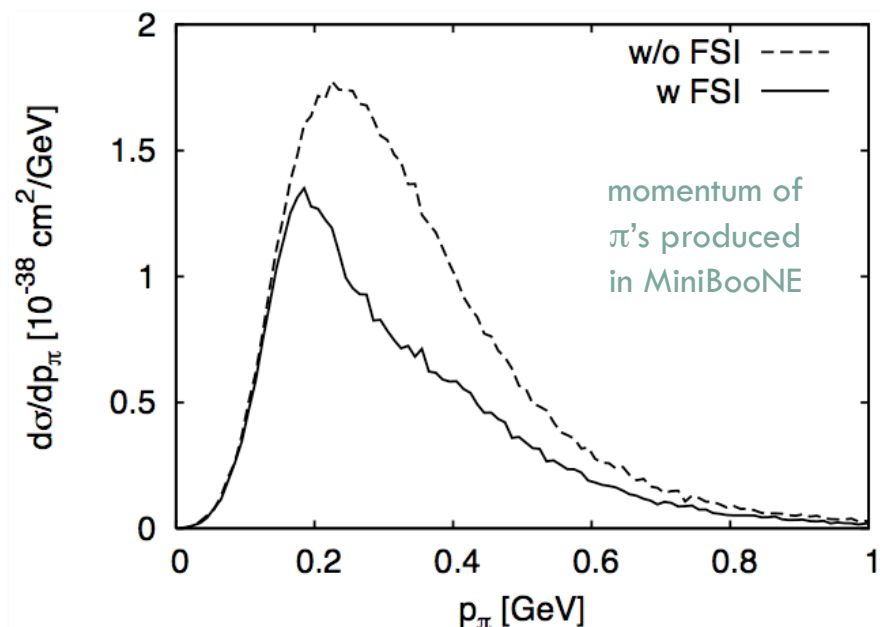
- <u>and predictions of their effects can vary</u>

http://regie2.phys.uregina.ca/neutrino/

x2!

momentum of π's produced in MiniBooNE

(T. Leitner)

- new FSI model work
  - GENIE (S. Dytman), GiBUU (U. Mosel), NEUT (P. dePerio)

- understanding π kinems is important
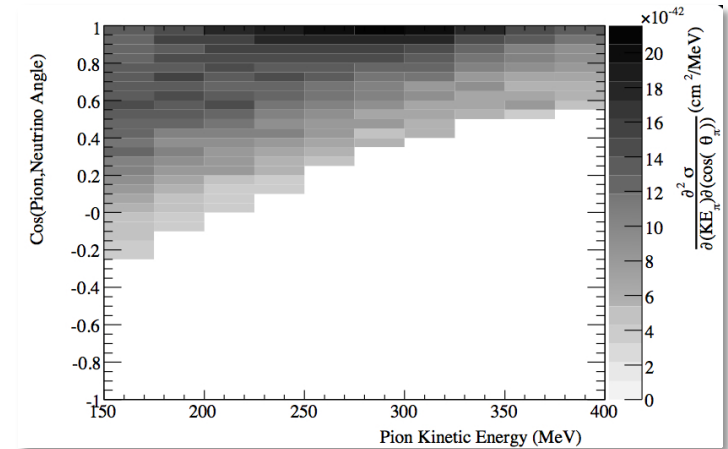 - has never been carefully studied in ν scattering

S. Zeller, PANIC, July 26, 2011

Pion Production in MiniBooNE

- extensive program to measure kinematics

  (report what is directly observed to reduce model dep)

(E. Zimmerman, parallel 1E)

- Phys. Rev. **D81**, 013005 (2010)
- Phys. Rev. **D83**, 052009 (2011)
- Phys. Rev. **D83**, 052007 (2011)

having this type of info is new!

measurement	NC π^0	CC π^0	CC π^+
$\sigma(E_\nu)$		X	X
$d\sigma/dQ^2$		X	X
$d\sigma/dp_\pi$	X	X	X
$d\sigma/d\cos\theta_\pi$	X	X	X
$d\sigma/dT_\mu$		X	X
$d\sigma/d\cos\theta_\mu$		X	X
$d^2\sigma/dT_\mu d\cos\theta_\mu$			X
$d^2\sigma/dT_\pi d\cos\theta_\pi$			X

- 3 channels, 16 different σ measurements!

- all of this data available online

  http://www-boone.fnal.gov/ for_physicists/data_release/

Example: CC π^0
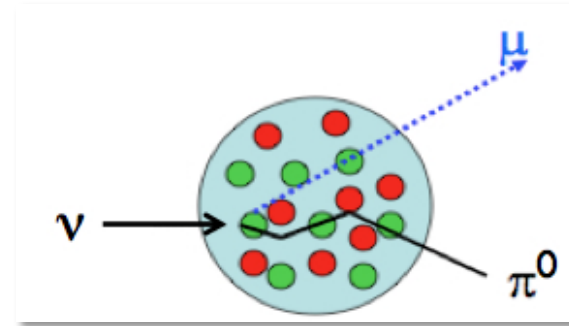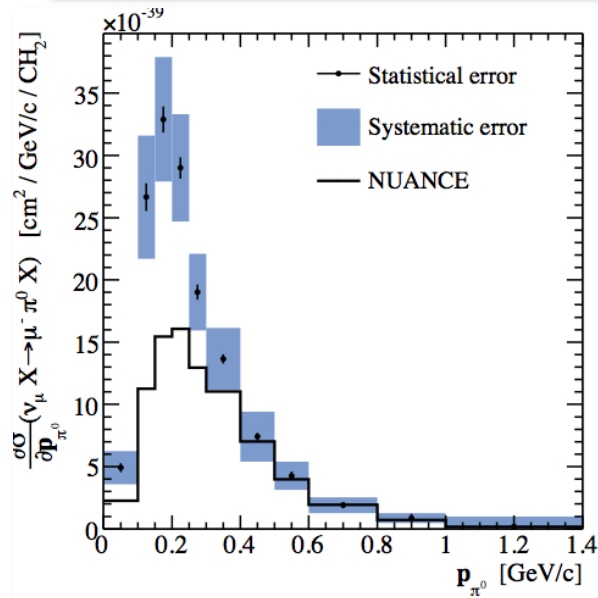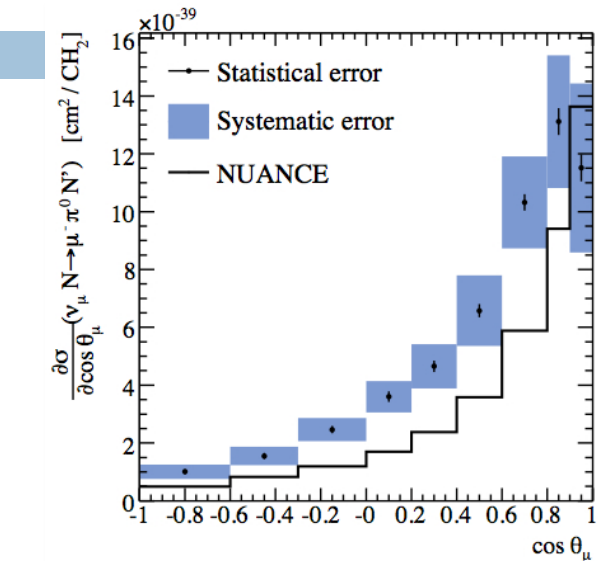
- 1st ever differential cross sections for this process on a nuclear target (CH_2)

$$\sigma(E_\nu), \ d\sigma/dQ^2$$
$$d\sigma/dT_\mu, \ d\sigma/d\theta_\mu$$
$$d\sigma/dp_\pi, \ d\sigma/d\theta_\pi$$

6 dists

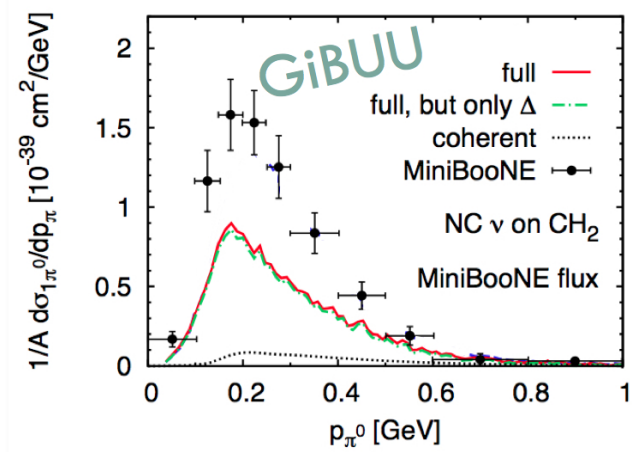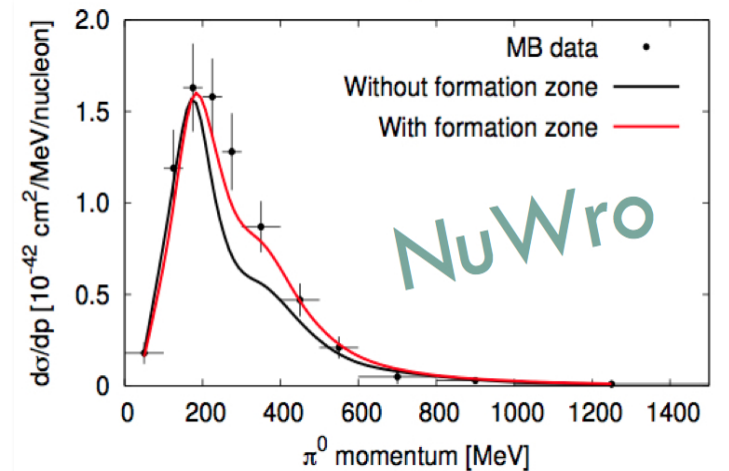- most comprehensive study of CC π^0 to date

FSI Models

- data in heavy use by model builders
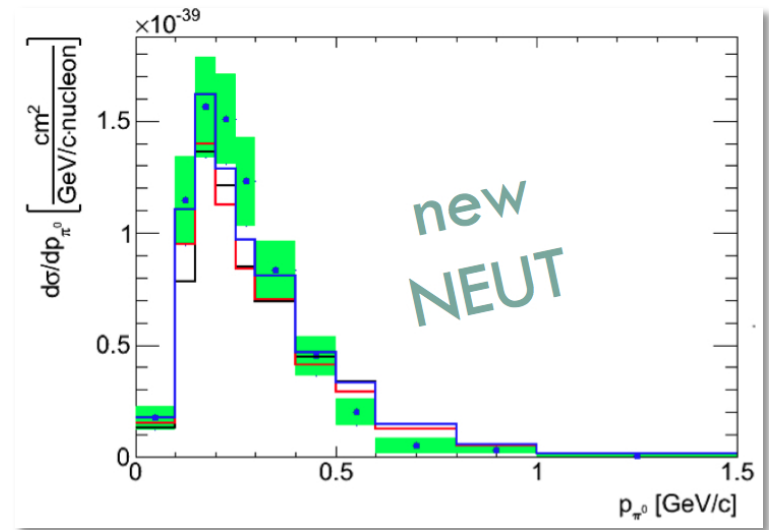
(U. Mosel)
arXiv:1106.1344 [hep-ph]

(T. Golan)

(P. dePerio)

- need measurements on other targets
- and at higher energies

  wish
  list

  - ArgoNeuT, ICARUS, μBooNE
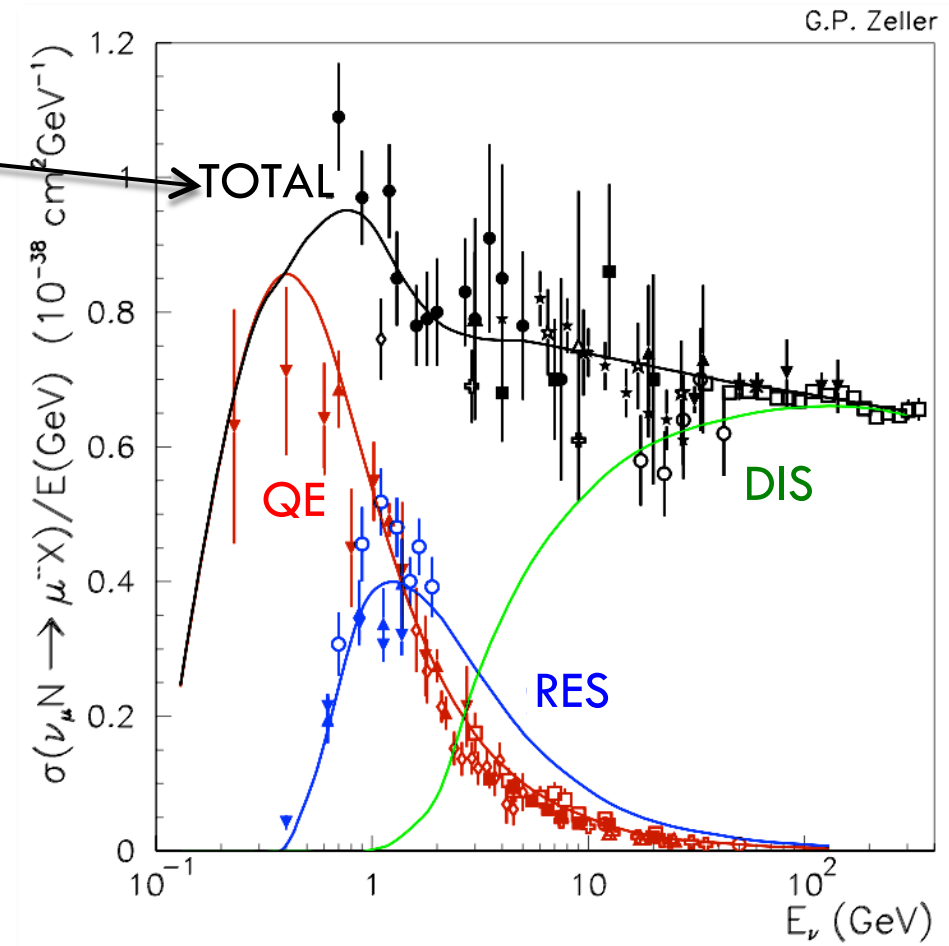 - MINERνA

- could use help from nuclear physicists!

Putting this All Together

- new appreciation for the role that **inclusive** measurements can play especially as we try to sift through these complex nuclear effects

G.P. Zeller

TOTAL

QE

DIS

RES

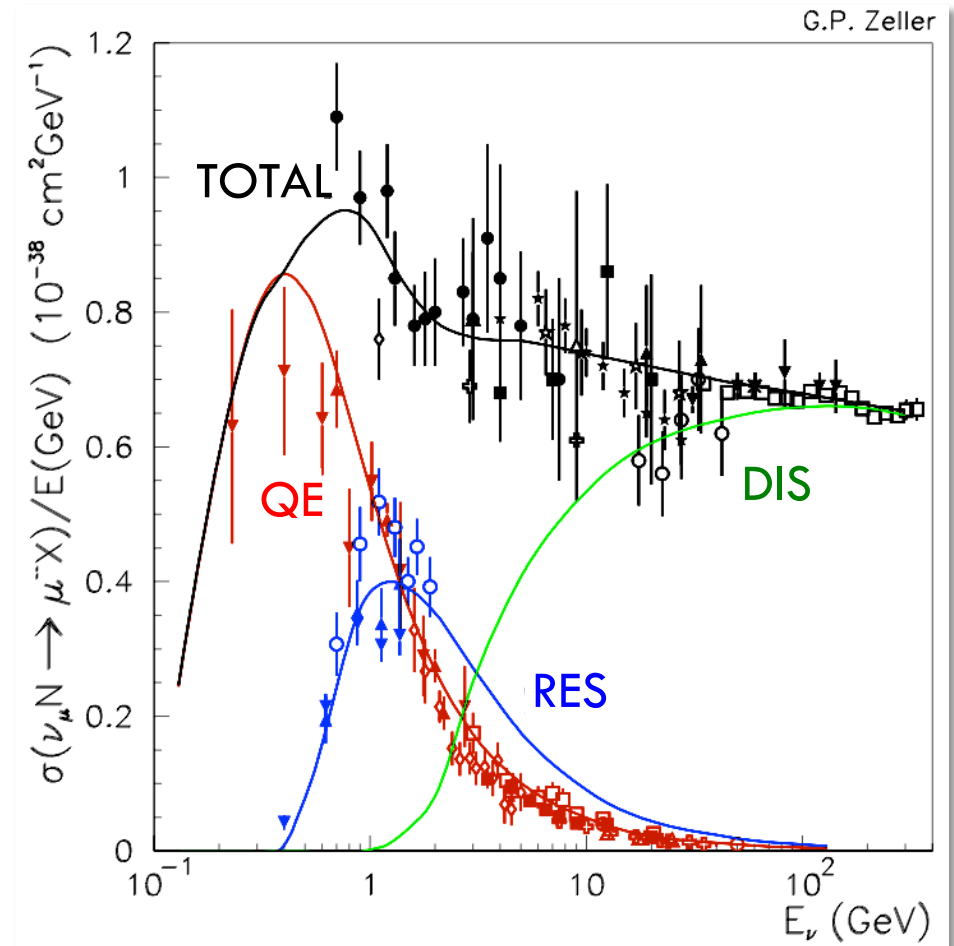$\sigma(\nu_\mu N \rightarrow \mu^- X)/E(\text{GeV})$ $(10^{-38}\ cm^2 GeV^{-1})$

E_ν (GeV)

CC Inclusive Cross Section

- advantage is that measures everything all at once:

+ QE
+ nucleon-nucleon correlations
+ π production
+ π absorption
+ DIS …

- can do so with very high purity samples (events with a μ)

G.P. Zeller

TOTAL

QE

DIS

RES

$\sigma(\nu_\mu N \rightarrow \mu^- X)/E(\text{GeV})$ $(10^{-38} \text{ cm}^2 \text{GeV}^{-1})$

E_ν (GeV)

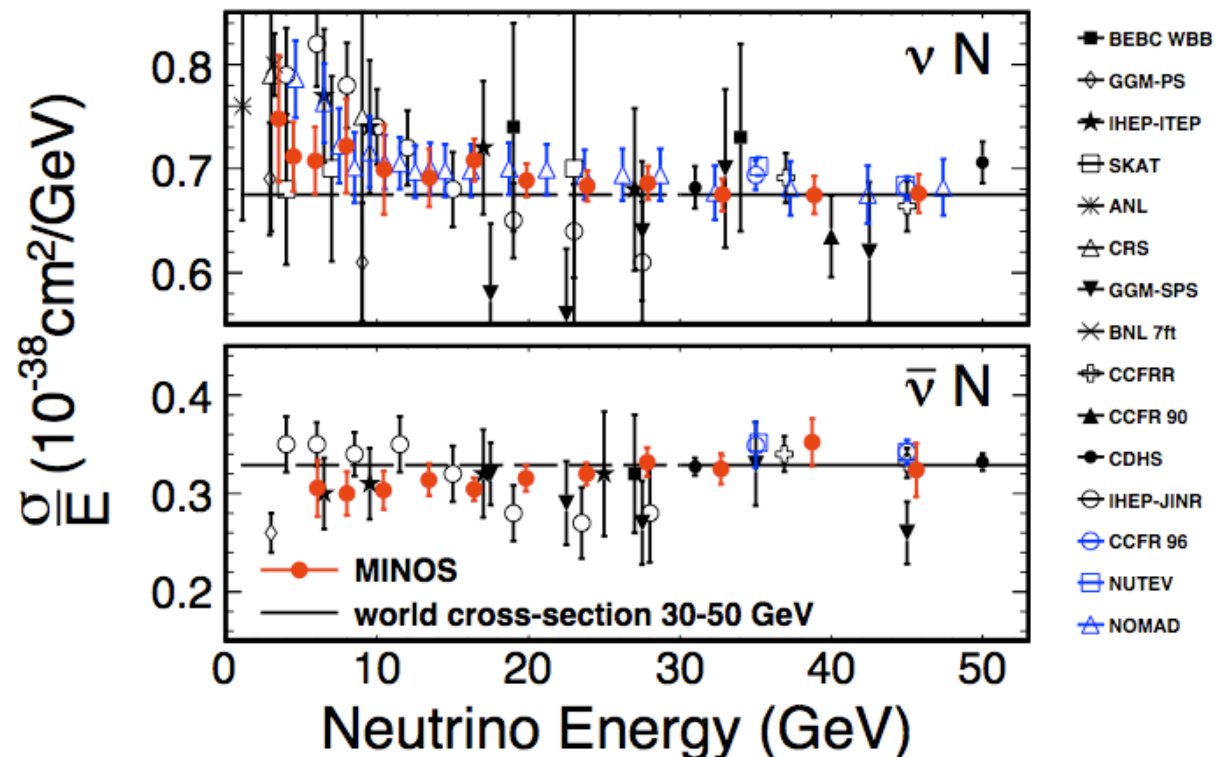clear need for improved measurements $E_\nu \lesssim 50$ GeV

CC Inclusive Cross Section

$$\nu_\mu\ N \rightarrow \mu^-\ X$$

- new data in the past couple years
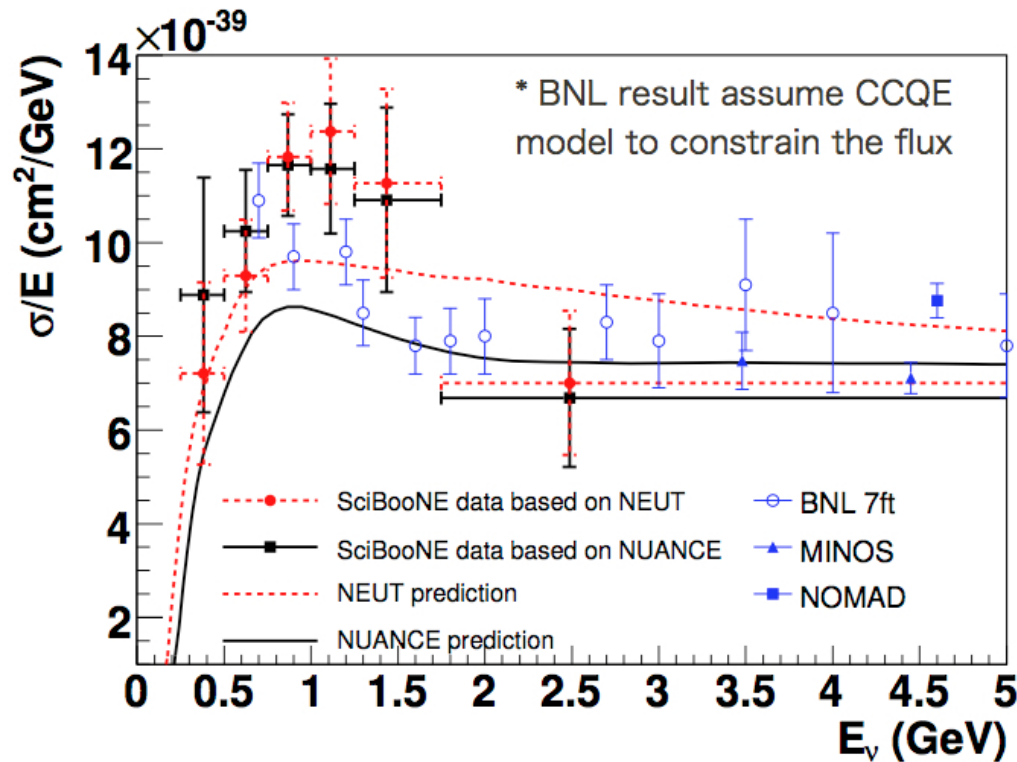
- have greatly increased precision in this energy region

- **NOMAD**: (ν ^{12}C) ... 4.5<E_ν<230 GeV ... PLB **660** 19 (2008)
- **MINOS:** ($\nu,\overline{\nu}$ ^{56}Fe) ... 3.5<E_ν<45 GeV ... PRD **81,** 072002 (2010)

CC Inclusive at SciBooNE

$$\nu_\mu N \rightarrow \mu^- X$$
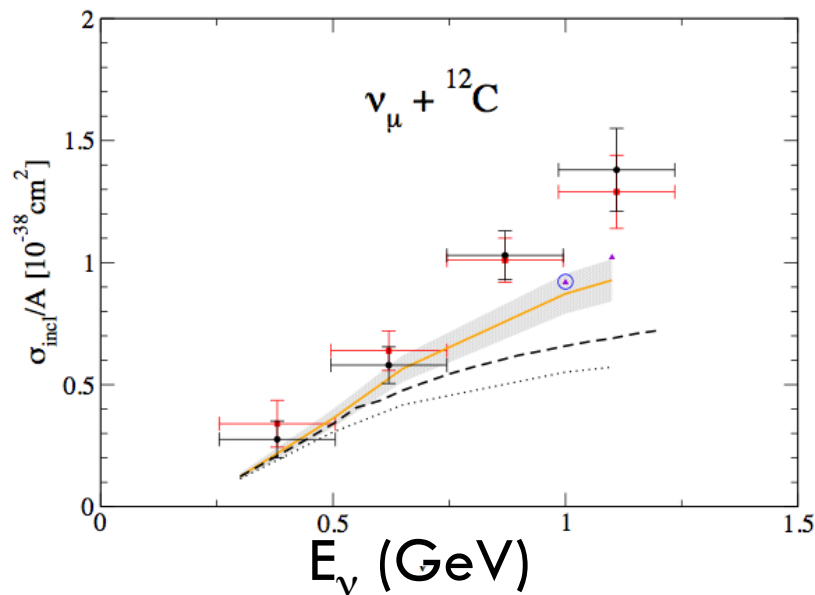
- more recently, SciBooNE published 1st measurement of CC inclusive σ on a nuclear target at low energy
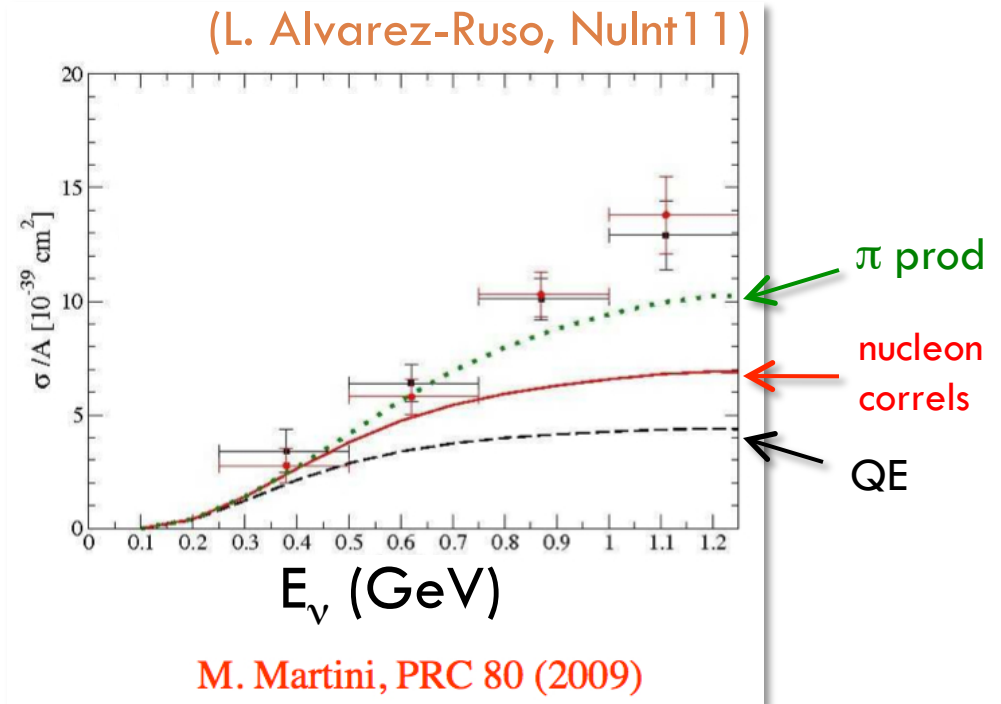
- CH, $E_\nu < 3$ GeV

Nakajima, *et al.*, PRD **83**, 012005 (2011)

SciBooNE Results in Use

- these data are a very useful starting point for model comparisons

(L. Alvarez-Ruso, NuInt11)

$\nu_\mu + {}^{12}C$

Nieves et al., arXiv:1102.2777

M. Martini, PRC 80 (2009)

π prod

nucleon correls

QE

wish list
- comparisons need to be extended out to higher energies
- need kinematic measurements, e.g. $d^2\sigma/dT_\mu d\theta_\mu$ (ala QE)
- need measurements on different nuclei (FSI vs. nucleon correls)
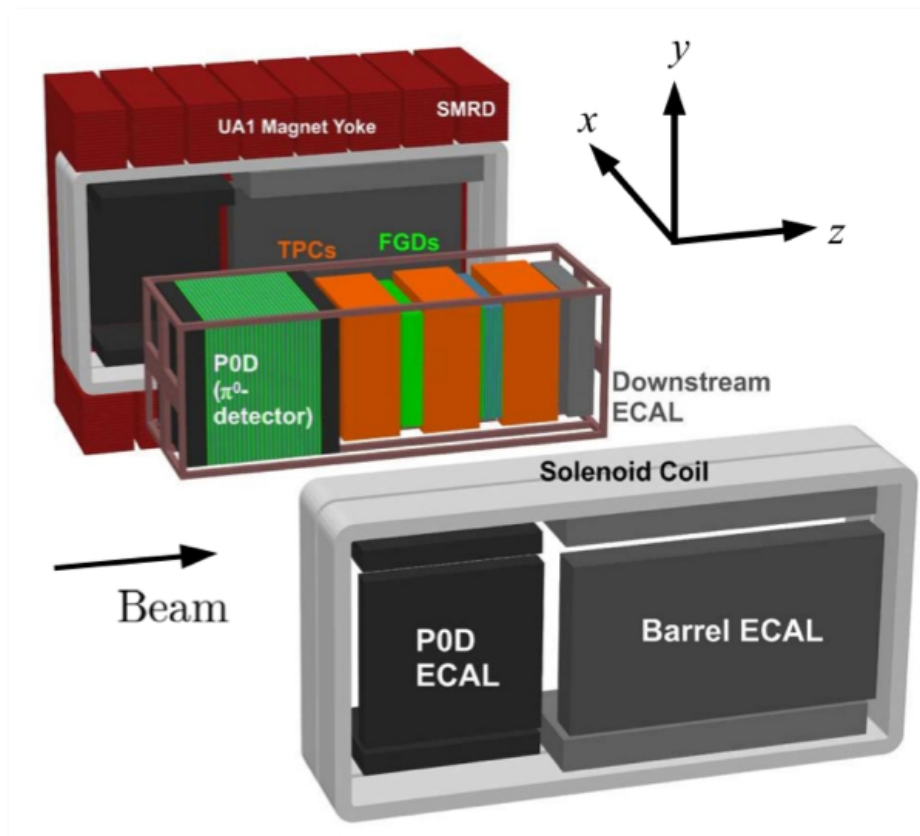
S. Zeller, PANIC, July 26, 2011
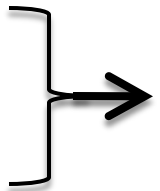
CC Inclusive at T2K

39

- ND280 off-axis detector began ν data-taking in March 2010
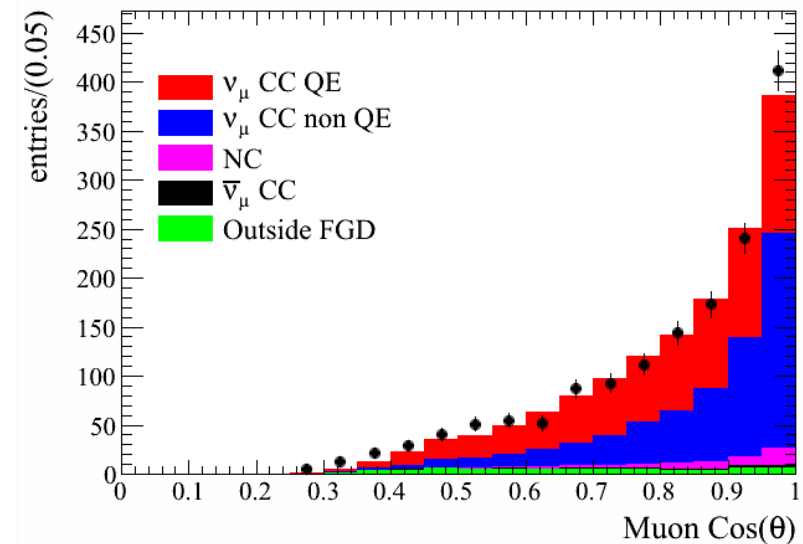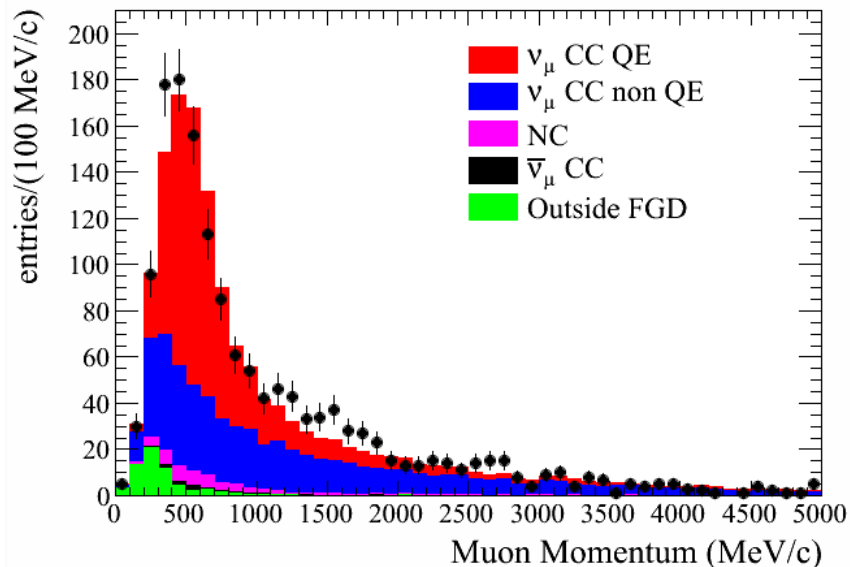 *(highlights importance of ND measurements which can weigh-in on these issues!)*

- low energy beam
  (very similar E_ν range to SB, MB)

- measurements on both C, O

- magnetized, fine-grained tracking detectors

S. Zeller, PANIC, July 26, 2011

CC Inclusive at T2K

• the first neutrino data from T2K ND has recently come out!

• ingredients for $d^2\sigma/dT_\mu d\theta_\mu$

• good agreement with NEUT
(tuned to prior ν data from K2K, SB)
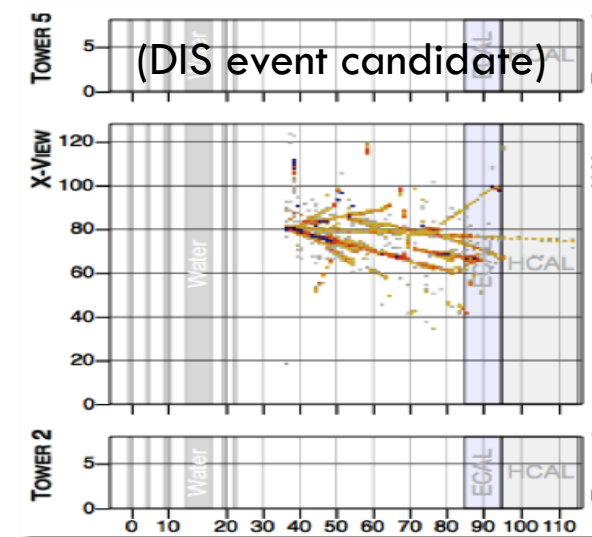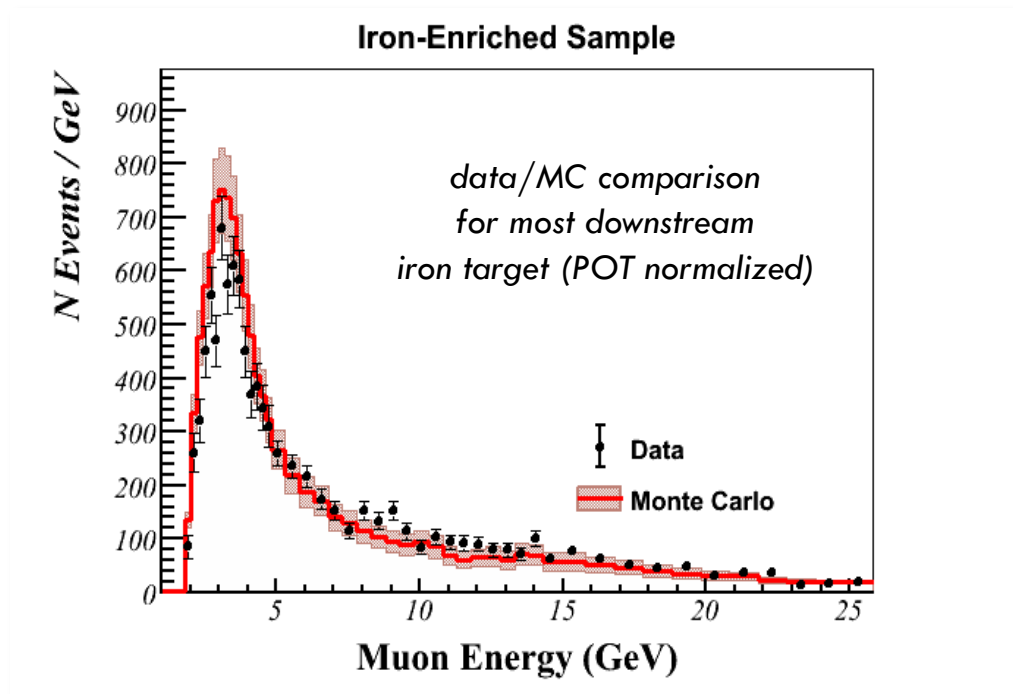
(B. Berger, parallel 2E)

CC Inclusive at MINERvA

- one of 1st goals is to measure CC inclusive σ ratios for various nuclei across very large energy range *(will be a real power house!)*

   - *LE mode alone*: 409k events CH, 68k Pb, 65k Fe

MINERvA 1st glimpse!

Iron-Enriched Sample

data/MC comparison for most downstream iron target (POT normalized)

Data
Monte Carlo

(DIS event candidate)
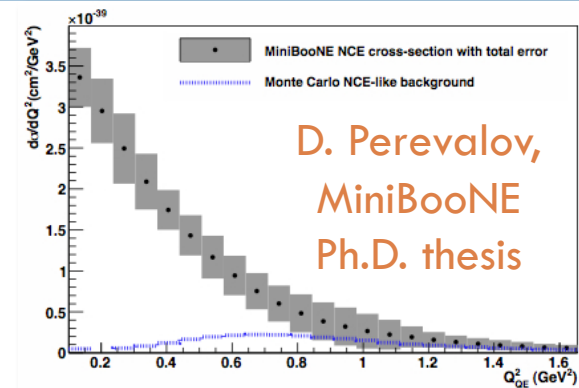
really nice data, plus
… much more to come!

(R. Ransome, parallel 2E)

Didn't Have Time To Discuss …

- NC elastic scattering (ν_μ N $\rightarrow \nu_\mu$ N)
  - **MiniBooNE**, PRD **82**, 092005 (2010)

D. Perevalov, MiniBooNE Ph.D. thesis

- NC coherent π^0 production (ν_μ A $\rightarrow \nu_\mu$ A π^0)
  - **MiniBooNE**, PLB **664**, 41 (2008)
  - **NOMAD**, PLB **682**, 177 (2009)
  - **SciBooNE**, PRD **81**, 033004 (2010), 11102 (2010)
  - **MINOS**, D. Cherdack, NuInt11 workshop

- CC coherent π^+ production (ν_μ A $\rightarrow \mu^-$ A π^+)
  - **K2K**, PRL **95**, 252301 (2005)
  - **SciBooNE**, PRD **78**, 112004 (2008)
  - **SciBooNE** $\overline{\nu}$, H. Tanaka, NuInt11 workshop

C. Kullenberg, NOMAD Ph.D. thesis
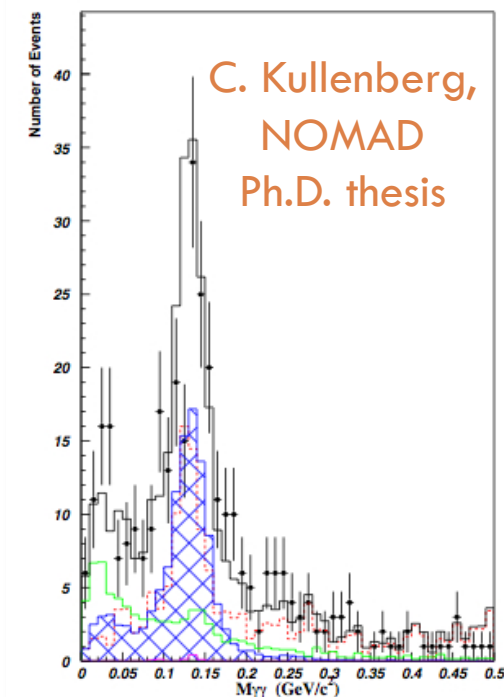
Conclusions

- there has been a surge of new results on a variety of different ν interaction channels from multiple exps in an important E region *(few-GeV)*
  (K2K ND, MiniBooNE, MINOS ND, NOMAD, SciBooNE)

- what was supposed to be boiler-plate physics has turned out to be far from that

    - *nuclear effects are important!*

* need continued help from theory community to better understand impact of these effects

* need add'l experimental measurements to provide both confirmation and clarity
  (ArgoNeuT, ICARUS, MicroBooNE, MINERνA, NOνA & T2K NDs)

NEUTRINO CROSS SECTIONS

stay tuned!

- $d\sigma/dx_{obs}$ in favor of $\sigma(E_\nu)$
- antineutrinos too!